A Thermochemical Regenerative Energy Storage System (TRESS)

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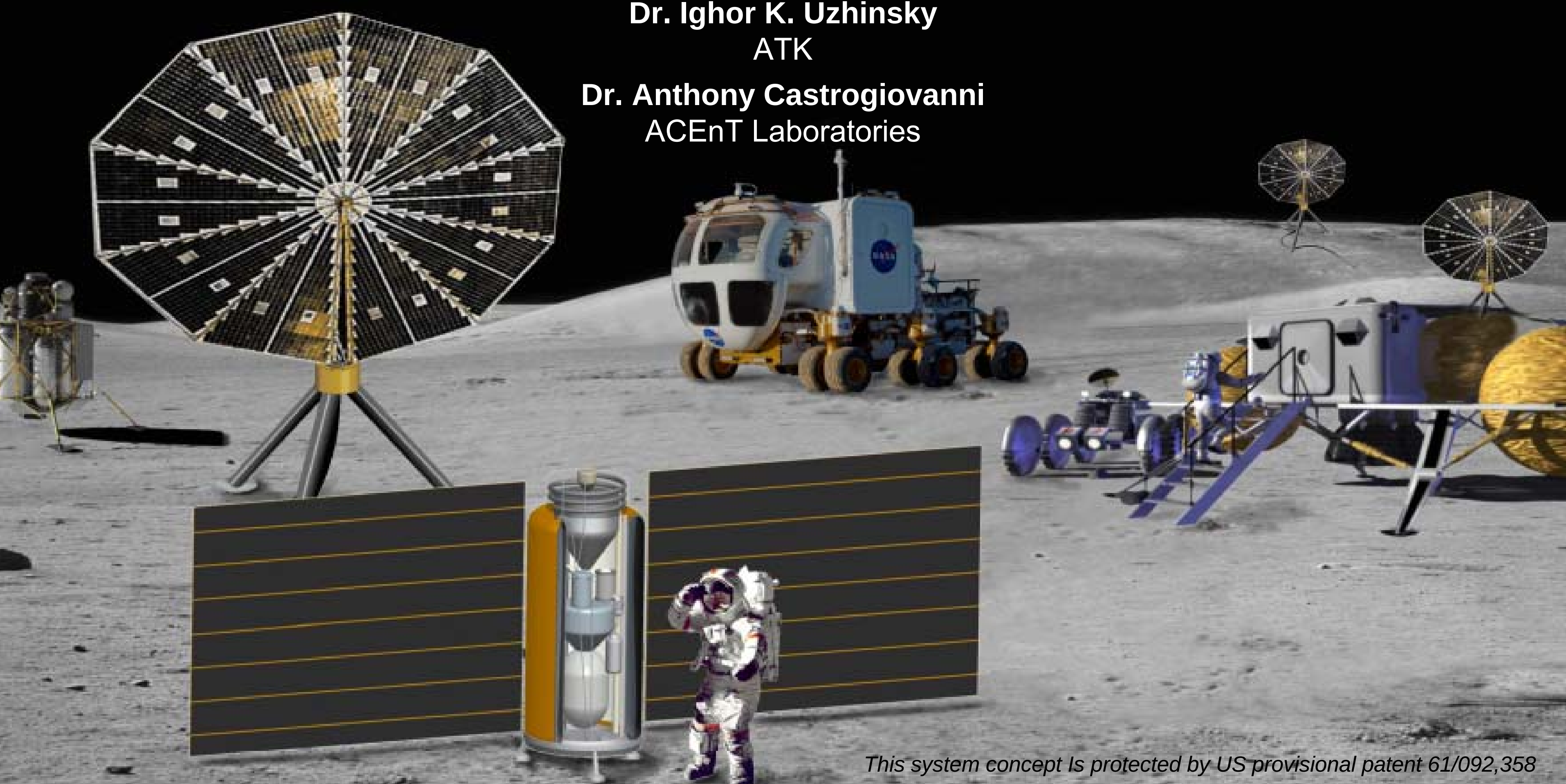

This system concept Is protected by US provisional patent 61/092,358

Acknowledgements

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- The authors would like to thank NASA for the opportunity to carry out the effort summarized in this report. Particular thanks are given to Mr. Patrick George of the Glenn Research Center for his role as contract technical monitor, providing valuable feedback and insights throughout the study.
- Additionally, this work could not have been carried out without the support of the following people:
  - Tom Cable, University of Toledo
  - Andrew Eckel, NASA Glenn Research Center
  - Timothy Norman, Giner Electrochemical Systems
  - Uday Pal, Boston University
  - Michael Rueter, Headwaters Technology Innovation
  - Doug Schmidt, Acumentrics
  - Scott Schwartz, NexTech
  - Bryan Seegers, M-DOT Aerospace
  - Al Sullivan, Headwaters Technology Innovation
  - Bing Zhou, Headwaters Technology Innovation

NNJ008TA80C Project Team

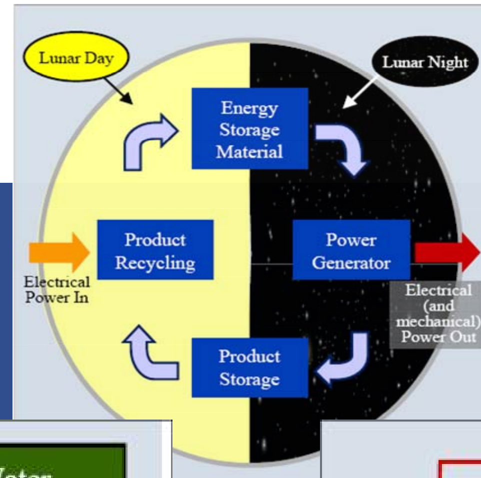
Program Manager – Dr. Ighor Uzhinsky (ATK)

Principal Engineer and Scientist – Dr. Tony Castrogiovanni (ACEnT Labs)

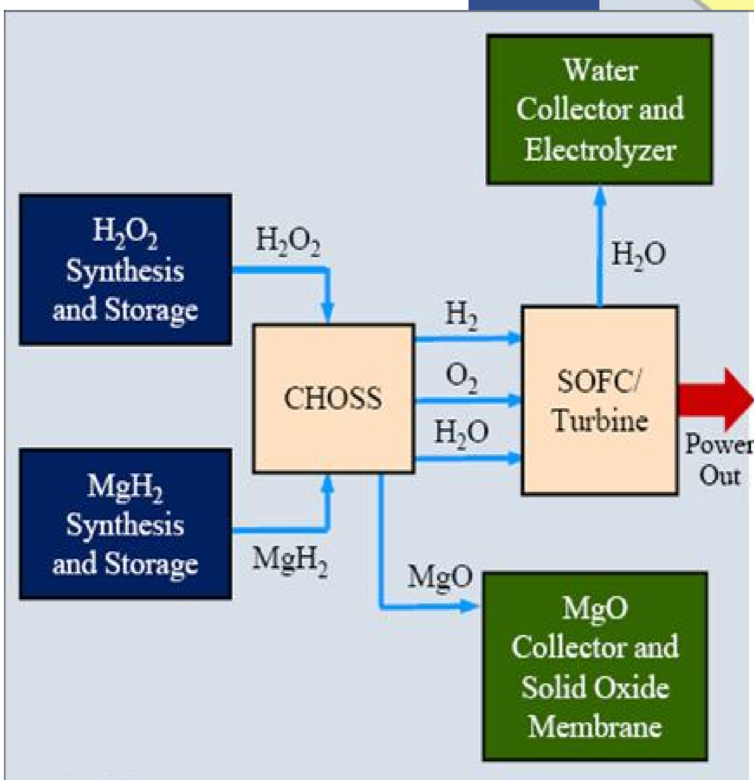
Key Subsystem Principal Investigators:

- Florin Girlea, Joe Alifano (ATK)
  - Provided engineering design data for H_2 generation reactor and 3D models of system
- Chris Kogstrom (ATK)
  - Investigated SOFC, turbine, and MgO recycling systems
  - Supported by Acumentrics, M-DOT Aerospace, and Boston University
- Dr. Akiva Sklar (ATK)
  - Led H_20_2 synthesis efforts supported by Headwaters Technology Innovation

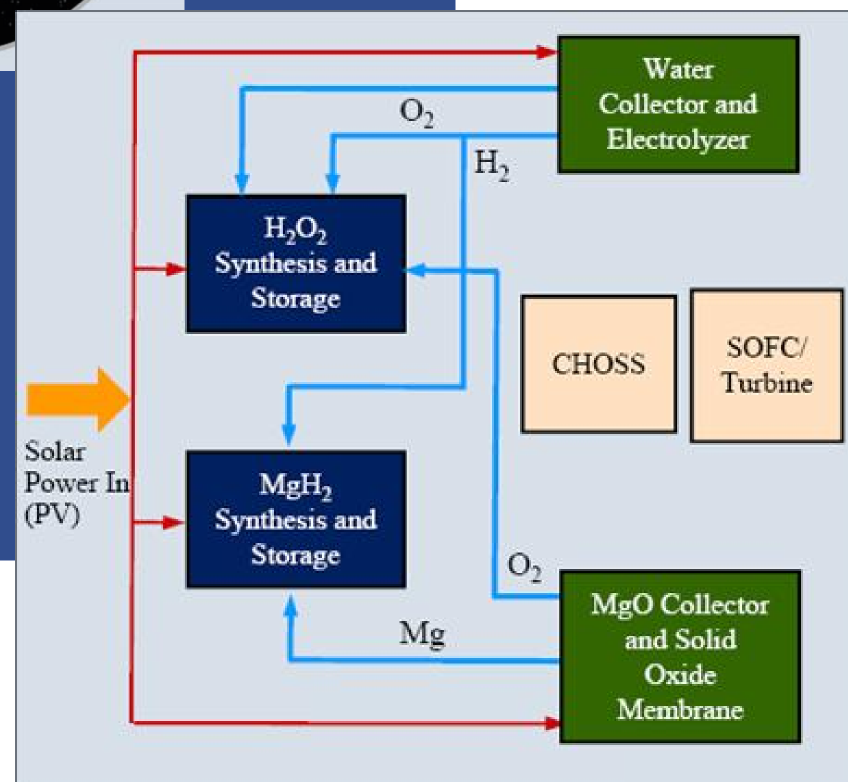
TRESS Night and Day Cycles



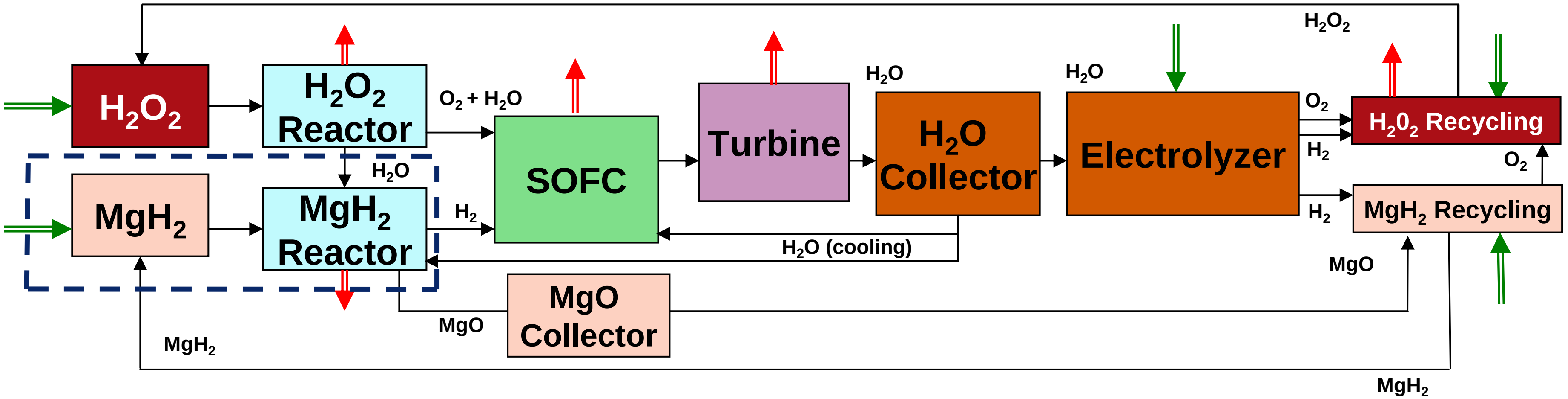
Night – Power Out



Day – Power In



TRESS Overview



$$2H_2O_2 \rightarrow O_2 + 2H_2O$$

$$MgH_2 + H_2O \rightarrow MgO + 2H_2$$

Concept based on efficient energy storage in hydrogen peroxide and magnesium hydride and in leveraging reaction heat release to generate hydrogen, oxygen, and steam for solid oxide fuel cell/steam microturbine power units

Reactant Volume Comparison

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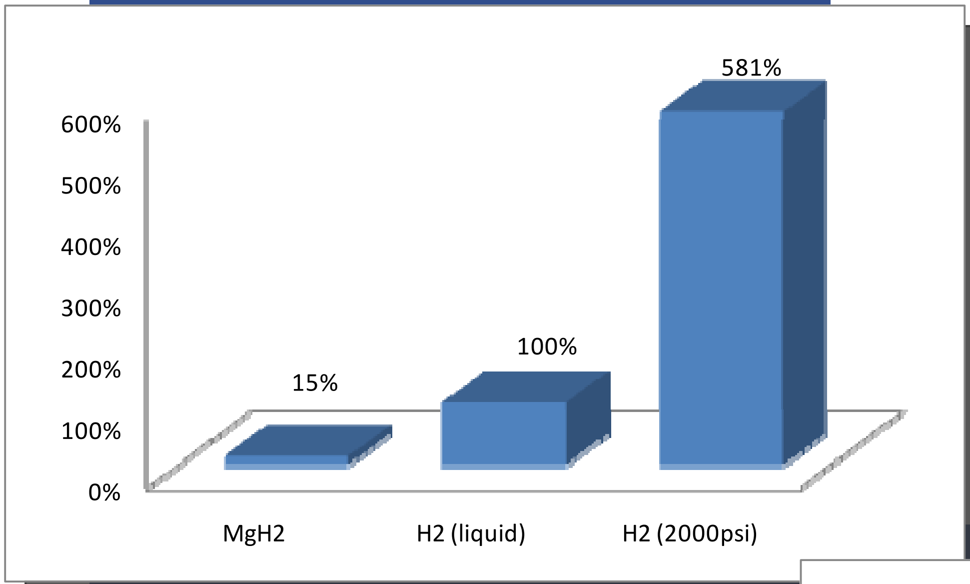

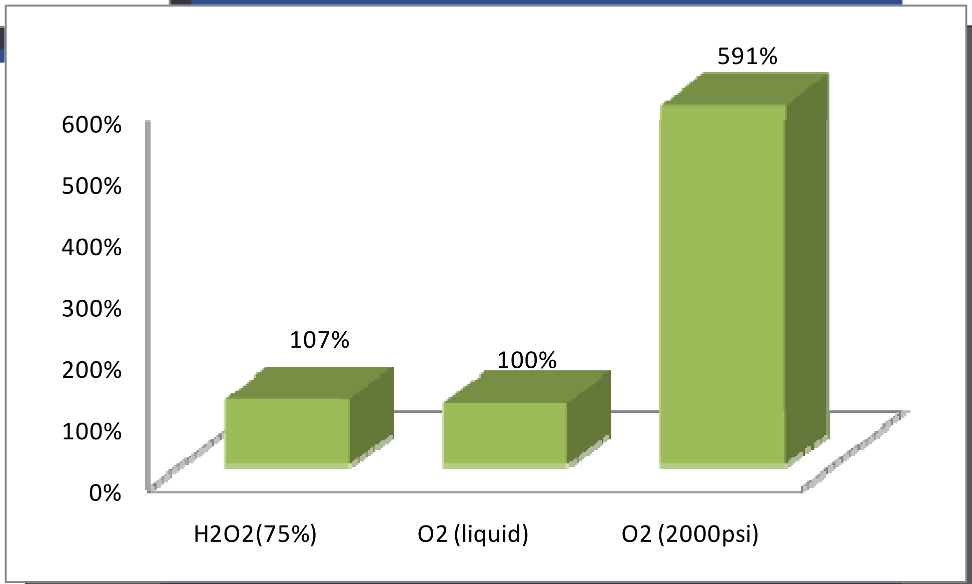

System Configuration – 5 kW, 2,000 kWh

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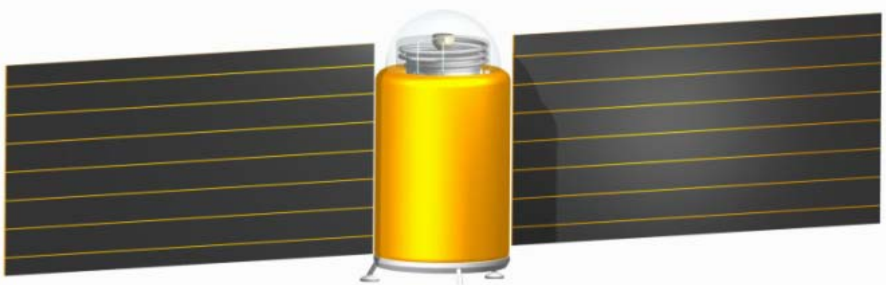
Pod configuration:

- Sealed from lunar environment in dome (radiation shield)
- Readily deployable from lander
- Electrical interfaces:
  - Power in from PV array
  - Power out
- Total system mass ≈ 2,000 kg
- Materials consumption:
  - MgH_2 powder: ~500 gram/hour
  - H_2O_2 (75% in water): ~1,800 gram/hour
- Fully regenerative closed system



TRESS Processes Benefits Summary

- High temperature chemical processes
  - High efficiency thermal energy conversion
  - High grade heat used to generate additional power
- High volumetric and gravimetric energy density
  - High efficiency storage of H_2 and O_2
  - Scaling-up storage (duration) increases overall system energy density
- Low material flow rates
  - Simplifies material supply subsystem components
  - Compact energy generation modules
- No maintenance required for materials stored for extended time periods
  - Opportunity to generate and store materials in advance for later use
  - Materials are safe and easily transportable
- Efficient material recycling technologies
  - System based on tested processes – need to develop lunar-specific designs
  - Experimental data are available to support system performance estimates
- Recycling process synergy with ISRU
  - Hydrogen peroxide may be used as a compact /storable water/oxygen source
  - MgO availability on the Moon

TRESS Unit Design Essentials

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- Compact size
  - The system can be delivered in one module to the Moon ready for operations after integration with the solar array
  - Most components (e.g. turbine/SOFC/H_2 and O_2 reactors) are small
  - The unit is transportable to other lunar locations

Mobile TRESS – 5 kW, 40 kWh (8-hour scenario)

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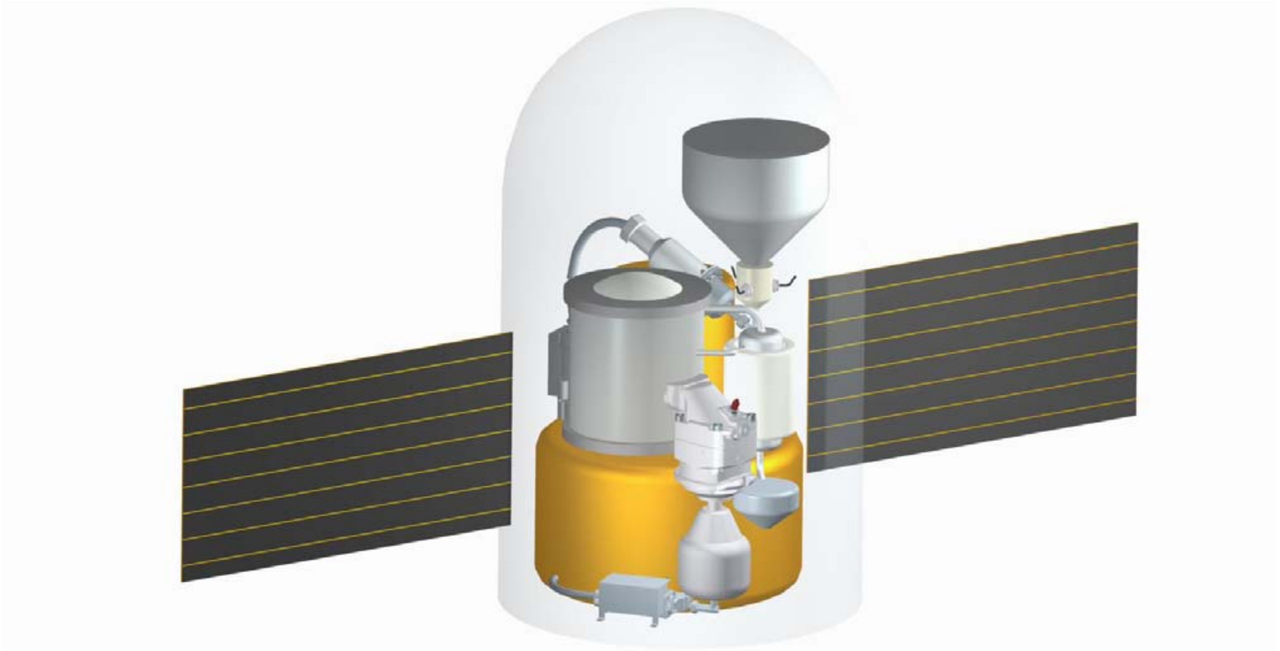
- Encapsulated fueling options
  - Provide opportunity to fuel mobile/remote units
  - May be readily transported via hoppers to any lunar location
  - Standardized recycling interface enables centralized recycling (recharging) pod



- System is ~18-in. Φ x 32-in. H + heat rejection panels
- Mass ≈ 80 kg (0.5 kWh/kg)

TRESS Mobile (Rover/Remote Outposts) Applications

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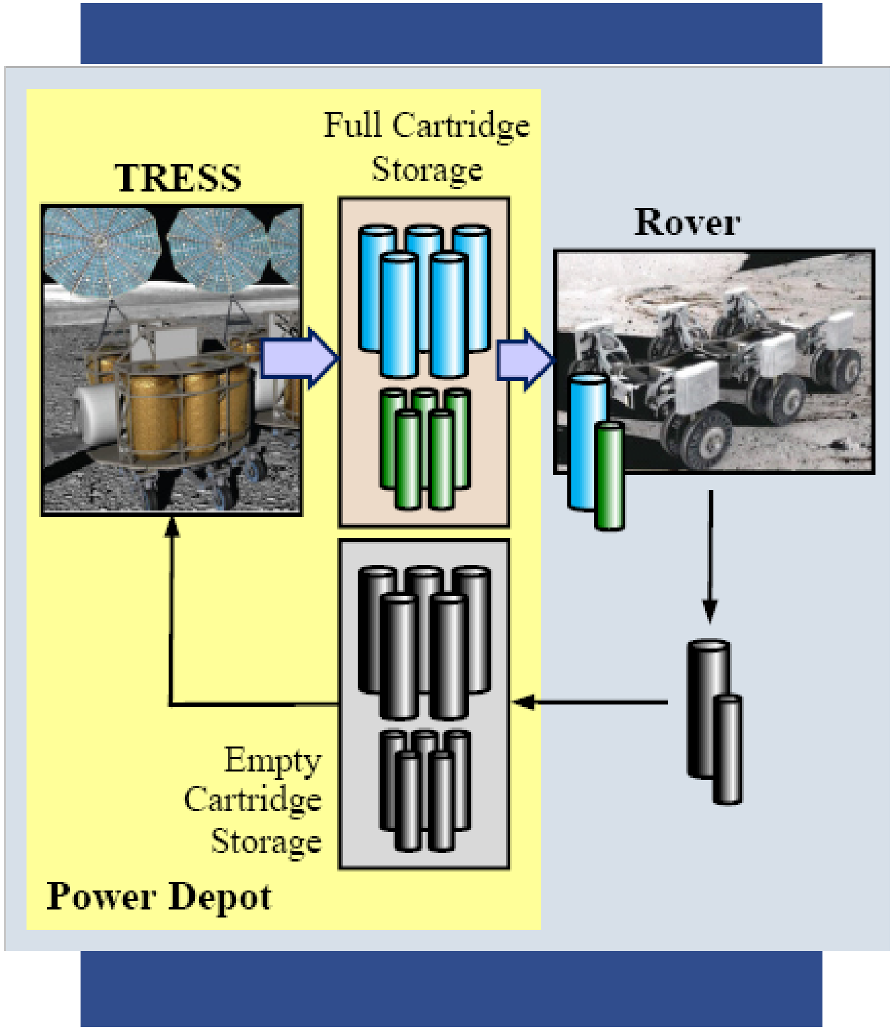
- Mobile units use encapsulated MgH_2 powder and peroxide cartridges that can be easily exchanged from a central depot or remote supply caches
- No need for on-board recharging
- Modular power cartridges may be distributed to any place on the lunar surface where common power generator interfaces are provided
- The cartridges are safe for long-term storage and may be delivered to the areas of interest in advance of particular missions



Applications/Variations of TRESS Technology

- $MgH_2 + O_2$ system (instead of H_2O_2)
  - Eliminates most complex synthesis process (and contaminants)
- Interplanetary Lunar Network (ILN)
  - <100 W systems for remote applications
- Emergency oxygen, water, or heat delivery
- Rocket propulsion using ISRU + TRESS derived propellants
  - $MgH_2 + H_2O_2$ rocket has Isp > 300 sec
- Terrestrial vehicle applications – compact H_2 for fuel cells and energy generators
- Underwater applications (or other sealed environments)

TRESS Relevance to Lunar Exploration Objectives

Category	Objective ID Number	Name	TRESS Technology Contribution
Life Support & Habitat	**mLSH2**	Develop and deploy closed loop life support systems to increase self sufficiency of future long duration human exploration missions and minimize the impact of humans on the environment.	TRESS technology of MgH2 and H2O2 generation from regolith and water should enable lunar base life support system for long-duration human exploration missions. Being recyclable these materials need only solar power for their reproduction in the originally available quantities minimizing regolith mining requirements and enviromental impact. TRESS energy generation system may become a universal modular solution for lunar base enrgy and life support.
General Infrastructure	**mGINF1**	Emplace support services on the Moon, including emergency response, to enable increased lunar activities.	As a result of "no-maintenance" storability of MgH2 and H2O2 and potential for delivery of capsules with these energetic materials and their universal use in energy generation/life support systems - emergency response may be provided even in remote locations during lunar expeditions.
	mGINF3	Deploy a Moon-based infrastructure that can service space-based assets to reduce the cost and increase the lifetime of space system operations.	With development of MgH2 /H2O2 propulsion systems (e.g. "Cold" solid rocket boosters) the lunar base may enhance its support for servicing of Moon orbiting and Earth/Moon space systems.
Operations, Testing & Verification	**mOPS3**	Establish crew-centered, real-time mission planning and control to enable self-sufficiency of lunar operations.	Because energetic materials in discussion may be generated in necessary quantities using regolith, water and solar energy then lunar base crew may plan activities and expeditions with less reliance to Earth-based resources and controls.
Power	**mPWRl**	Develop lunar power generation, storage, and distribution systems to satisfy the energy demands of lunar operations.	This is primary application for the TRESS system. We see this system as complimentary to RFC power units. Advantages of the TRESS energy storage and generation solution is in low-maintenance storage of the energetic materials that should be beneficial for long-term out-of-grid, shadowed locations.
Transportation	**mTRANS3**	Develop cryogenic fluid management, storage, and distribution systems to extend the lifetime and reduce the launch mass of exploration systems.	If TRESS energetic materials would have been produced and available in large quantities for use for long-term energy generation, intra-lunar transportation inculuding hoppers and rovers, emergency deliveries, and, potentially, propulsion - then requirements for cryogenic storage and distribution systems may be significantly reduced and simplified.

TRESS Relevance to Lunar Exploration Objectives

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Category	Objective ID Number	Name	TRESS Technology Contribution
Surface Mobility	mSM1	Provide surface mobility capabilities to move crew outside the local area of a lunar outpost.	TRESS-based infrastructure and energy generation units should provide a compact/high power propulsion systems for moon rovers and other lunar outpost vehicles. Encapsulated materials can be easily delivered to remote locations. Hydrogen peroxide alone is a perfect life-support material suitable for emergency needs providing energy, water, and oxygen.
	mSM2	Provide surface mobility capabilities to move cargo and equipment outside the local area of a lunar outpost.	See above.
	mSM3	Provide surface mobility capabilities for local operations within a lunar outpost complex.	See above
Lunar Resource Utilization	mLRU3	Develop and validate tools, technologies and systems that extract lunar resources, to enable lunar resource utilization.	Recycling technologies and equipment, being essential parts of the TRESS technology, should provide a compact and high efficiency units for processing of lunar extracted materials (regolith and water). SOM process is suitable for separation of oxygen and metals from a variety of oxides that are available on the Moon.
	mLRU4	Develop and validate tools, technologies and systems that process lunar resources, to enable lunar resource utilization.	TRESS technology is an example of development and validation of tools, software, components and systems that perform various engineering processing of extracted lunar resources. TRESS processes and technologies being implemented, reduce the mass of materials and products that must be launched from Earth for activities on the Moon and other destinations.
	mLRU6	Develop, validate, and incorporate new products and associated technologies and systems that effectively utilize lunar resources and products, to support further lunar resouce utilization.	See above. "Cold" solid rocket boosters that potentially may be fabricated on the Moon with TRESS energetic materials may enhance launch capabilities from the Moon base that are essential for the Mars program.
	mLRU7	Produce propellants and life support and other consumables from lunar resources, to improve the productivity of lunar operations.	TRESS concept, technologies, and equipment, being implemented, should ensure energy independence and life support to the whole cycle of lunar base operations and generationg of a significant stock of enegetic materials for variatty of applications (see above).

TRESS Relevance to Lunar Exploration Objectives

Category	Objective ID Number	Name	TRESS Technology Contribution
	mLRU8	Construct facilities and manufacture hardware, materials, and other infrastructure growth products and capabilities from lunar resources, to improve the productivity of lunar operations.	See above.
	mLRU9	Repair, fabricate and assemble parts and products using extracted and processed in-situ resources to support self-sustained, long duration missions.	See above.
	mLRU10	Produce products from lunar resources that can be used for missions to other destinations, to enable and support future exploration.	See above.

TRESS Program Plan Concept

- ATK and ACEnT Laboratories propose a phased program for the development of a TRESS system with a TRL of 6 by 2015 to 2018. The program is divided into 3 phases as follows:
  - Phase I: Electrical Energy Generating Module Demo and TRESS System Analysis
  - Phase II: TRESS Small Scale Prototype Demo Fabrication and Testing
  - Phase III: Full-scale TRESS Prototype Development, Design, and Testing
- Detailed schedules have been developed for each of the program phases using Microsoft Project software
- All work is expected to be conducted in close cooperation with NASA

TRESS System Design and Concept of Operation

TRESS Pod with Heat Rejection Arrays

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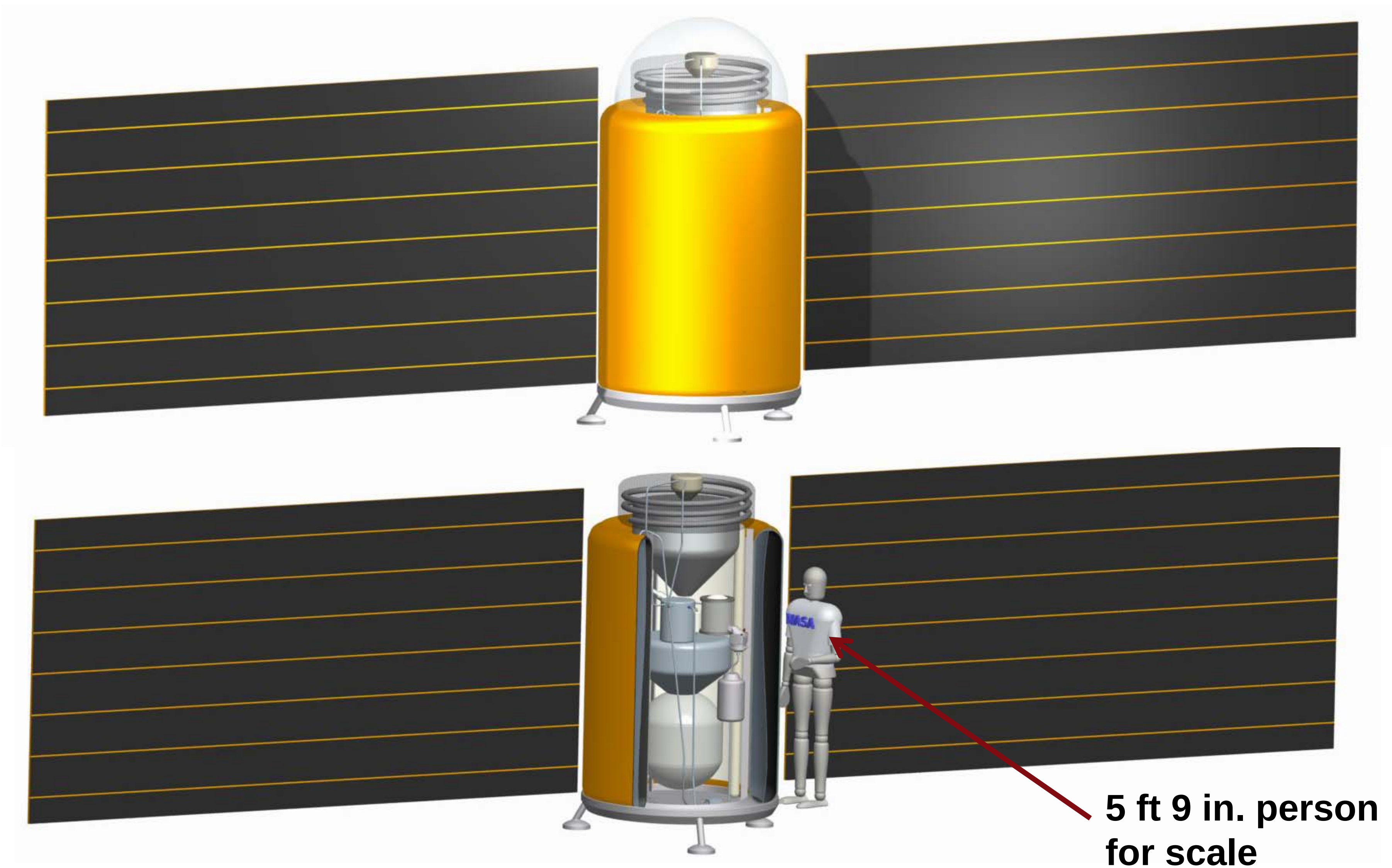
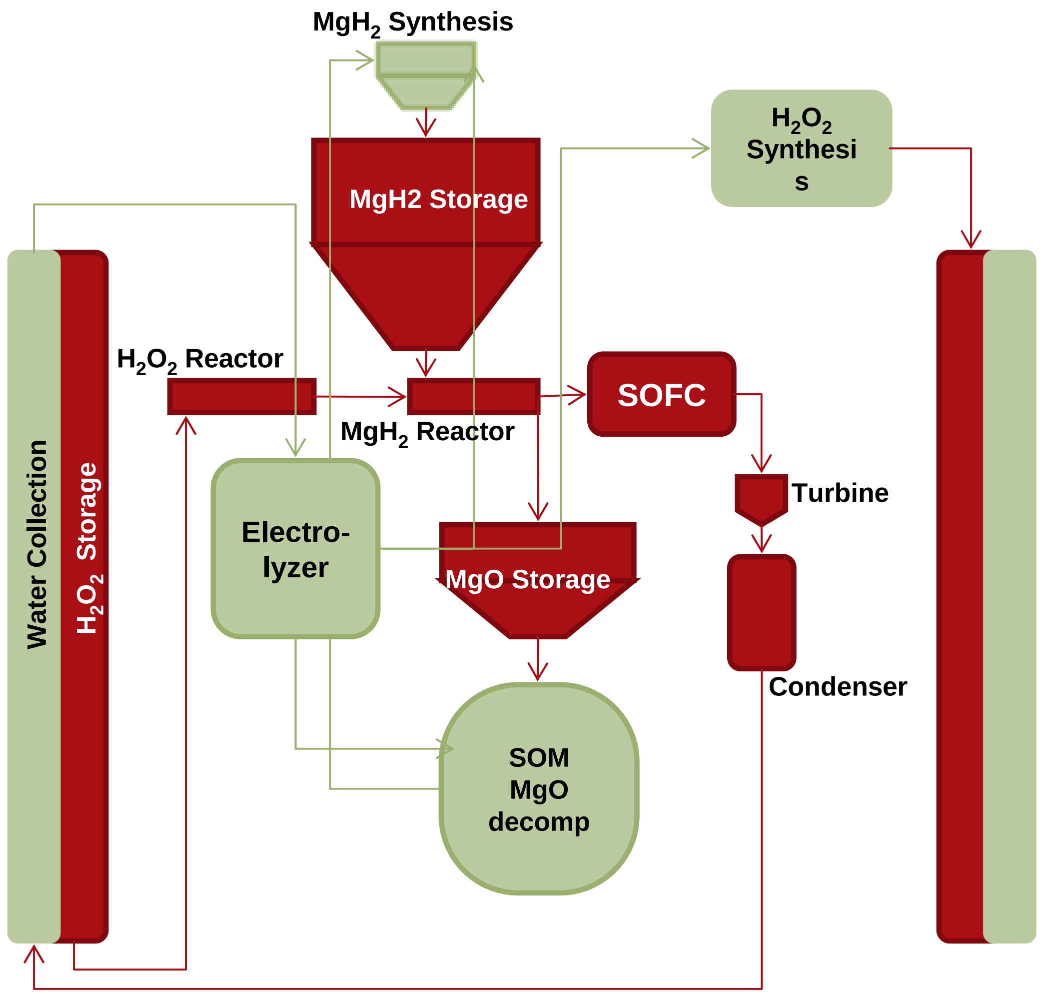
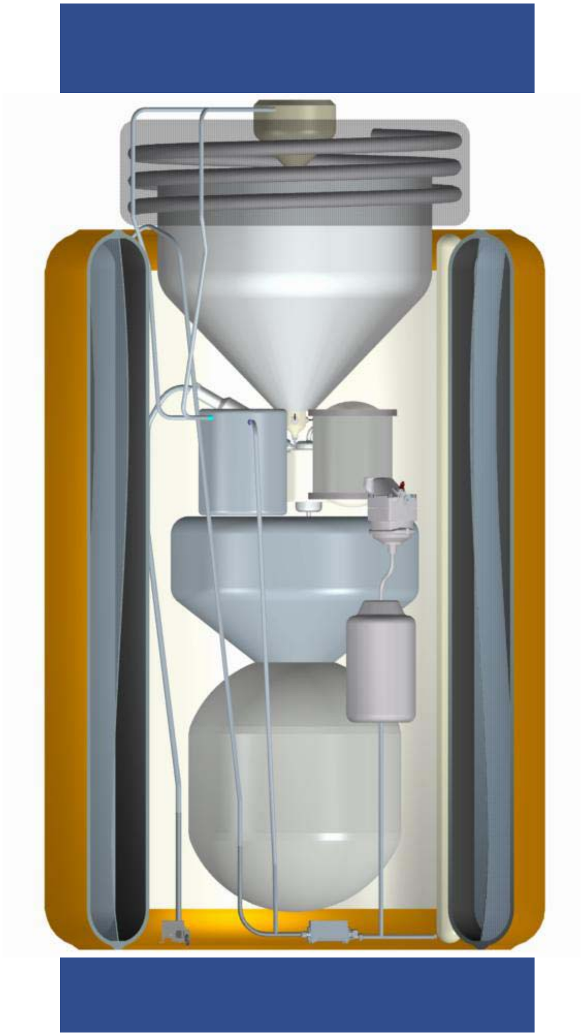


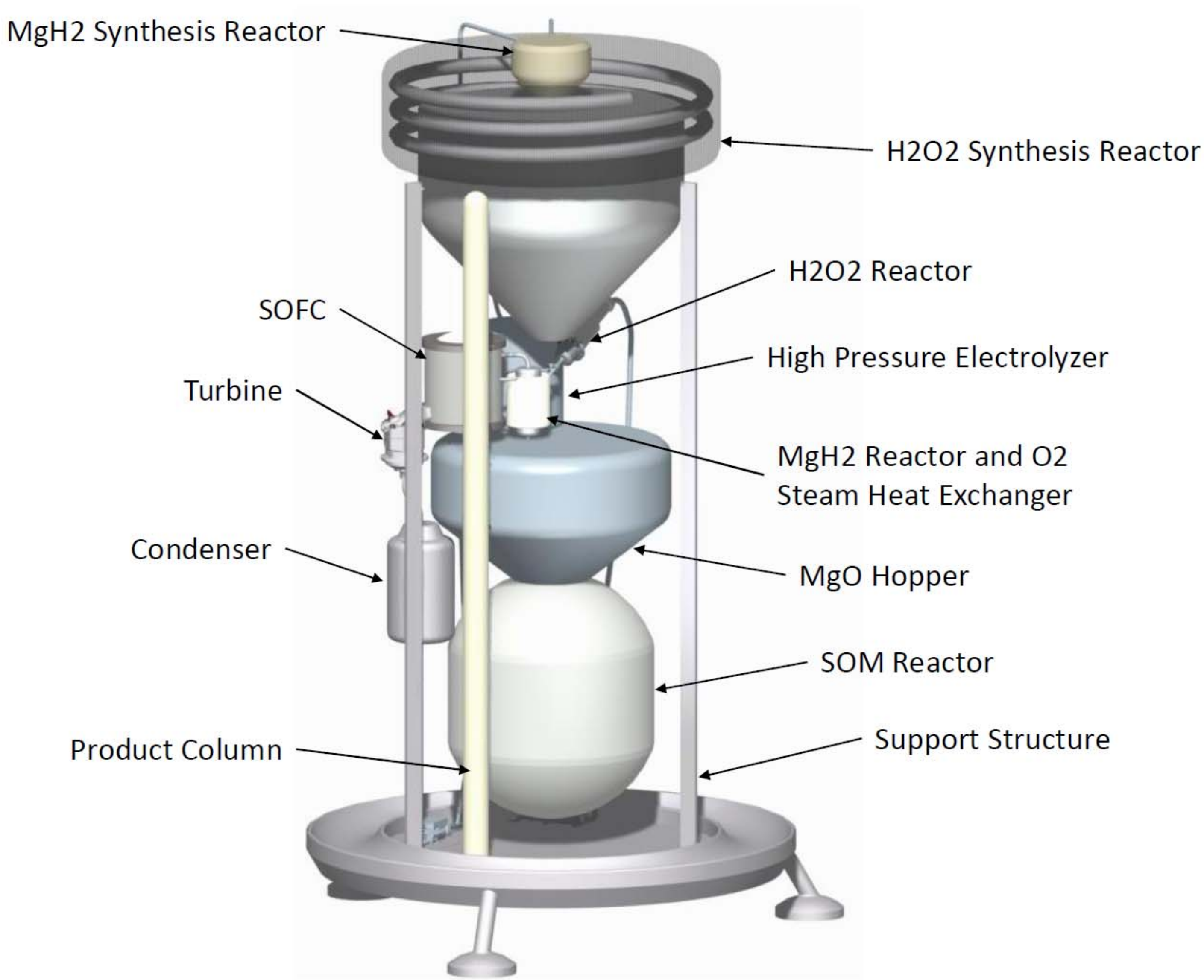
5 kW, 2,000 kWh System Depicted

System Block Diagram with Orientation





TRESS System Isometric (Peroxide Tank Removed)



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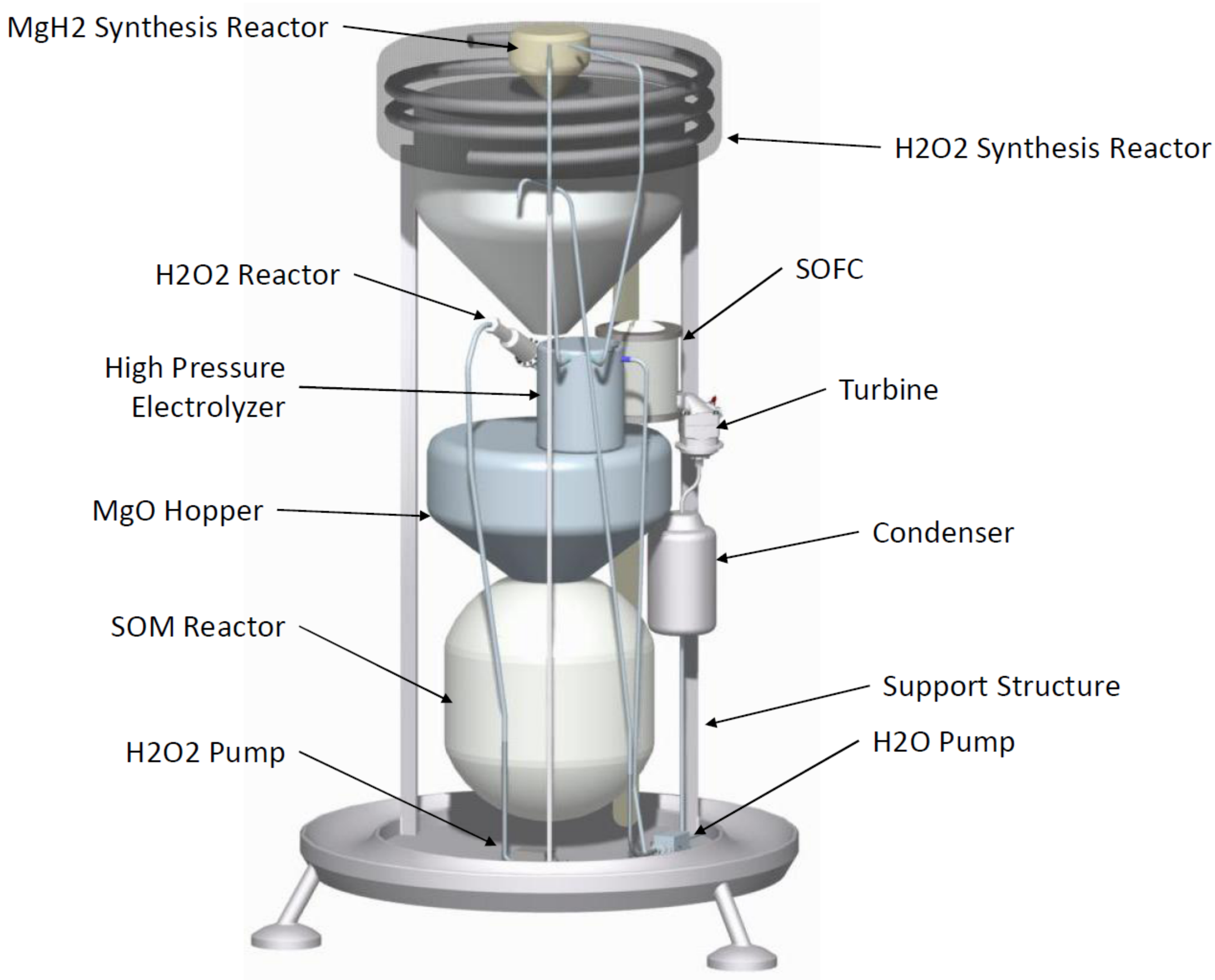

Mobile TRESS Block Diagram with Orientation

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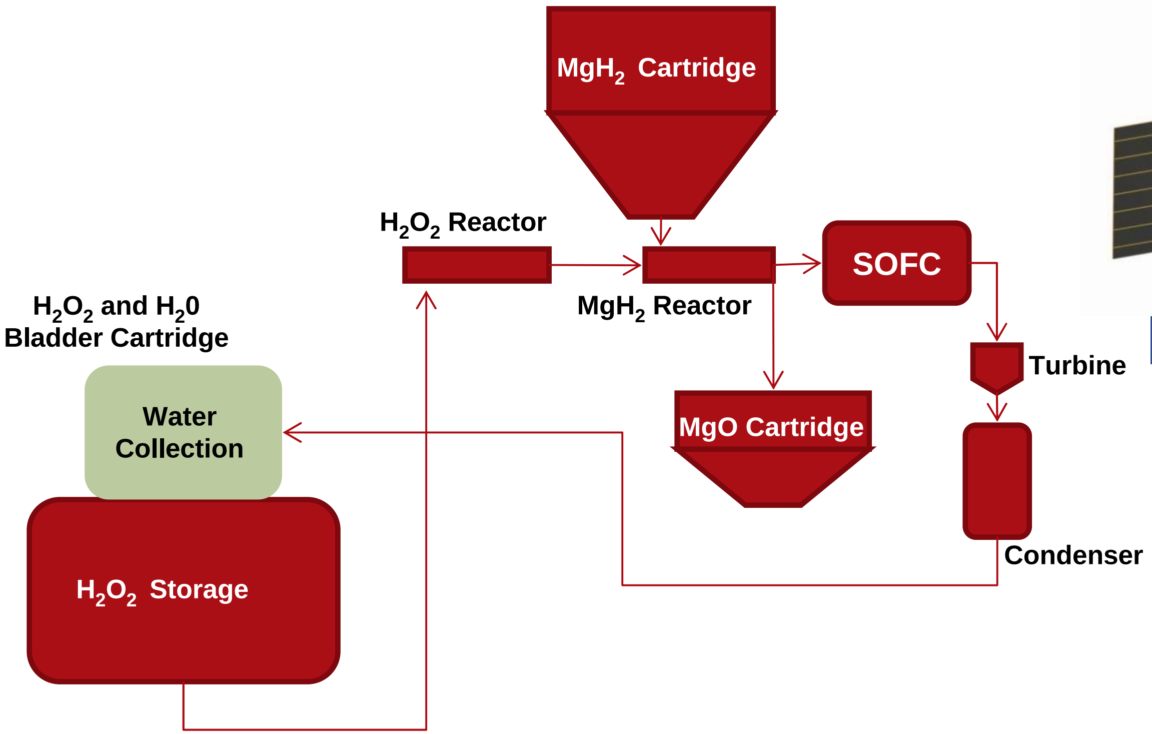

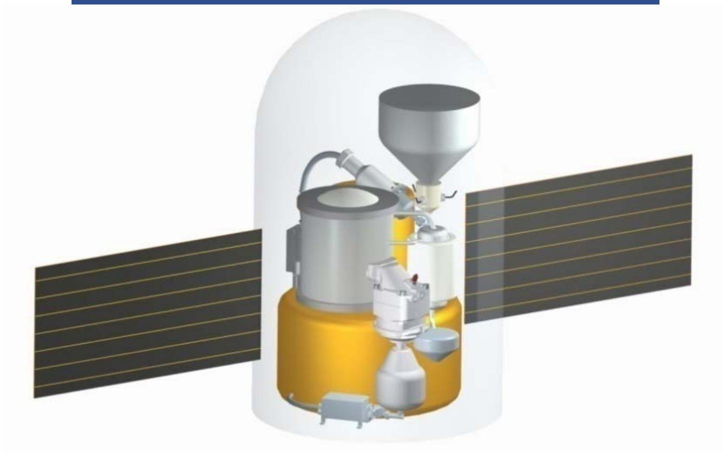

Only TRESS Power Generation Components Required for Mobile Applications

Regeneration Station for Mobile System

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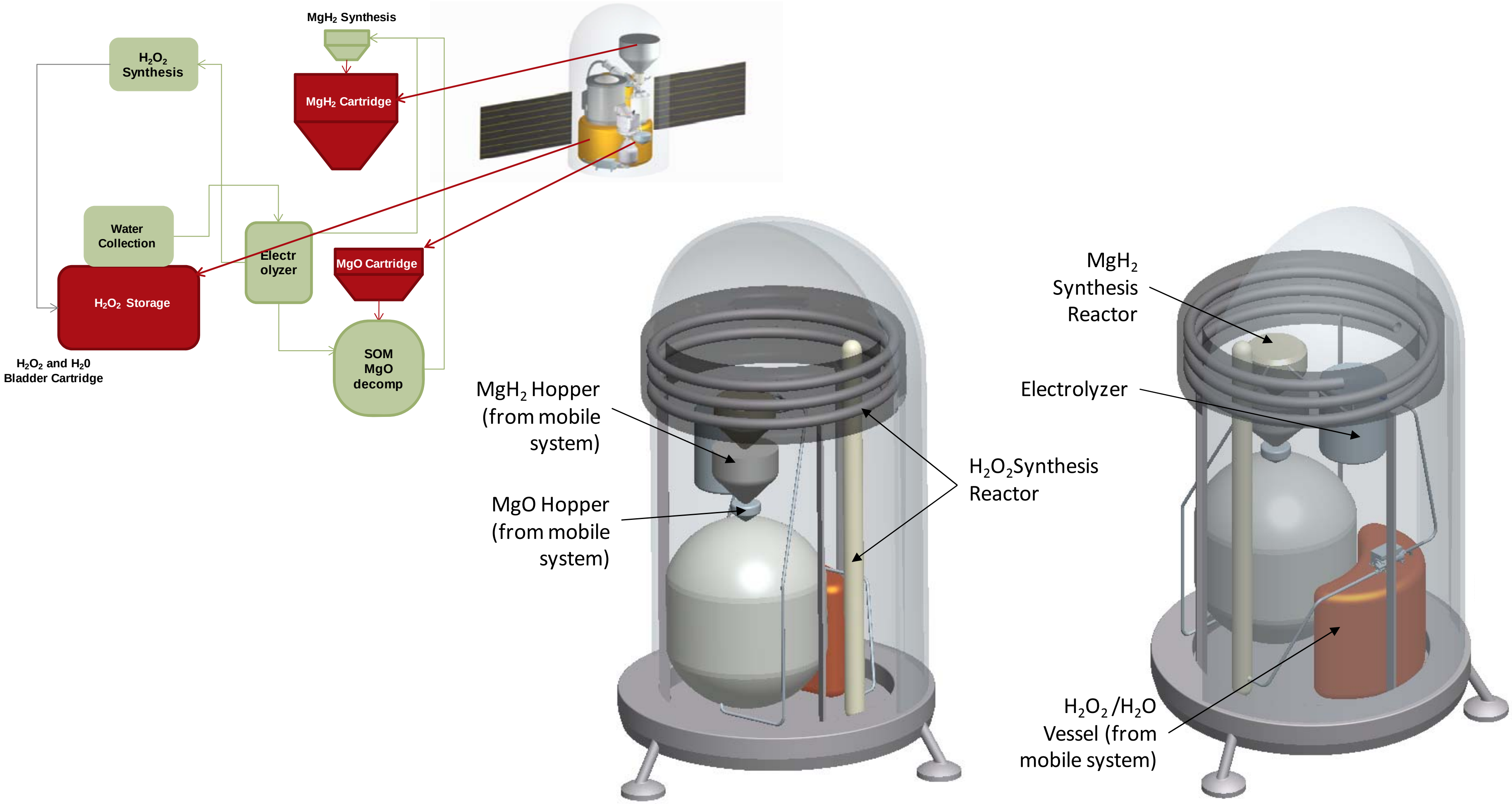

Mobile Cartridges are Inserted into Regeneration Pod

Subsystems Overviews

Aqueous Peroxide Storage

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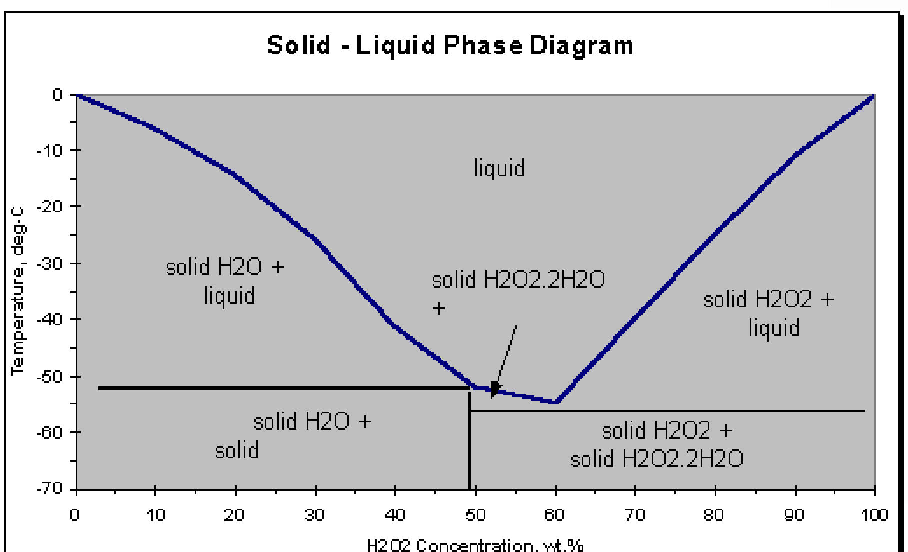
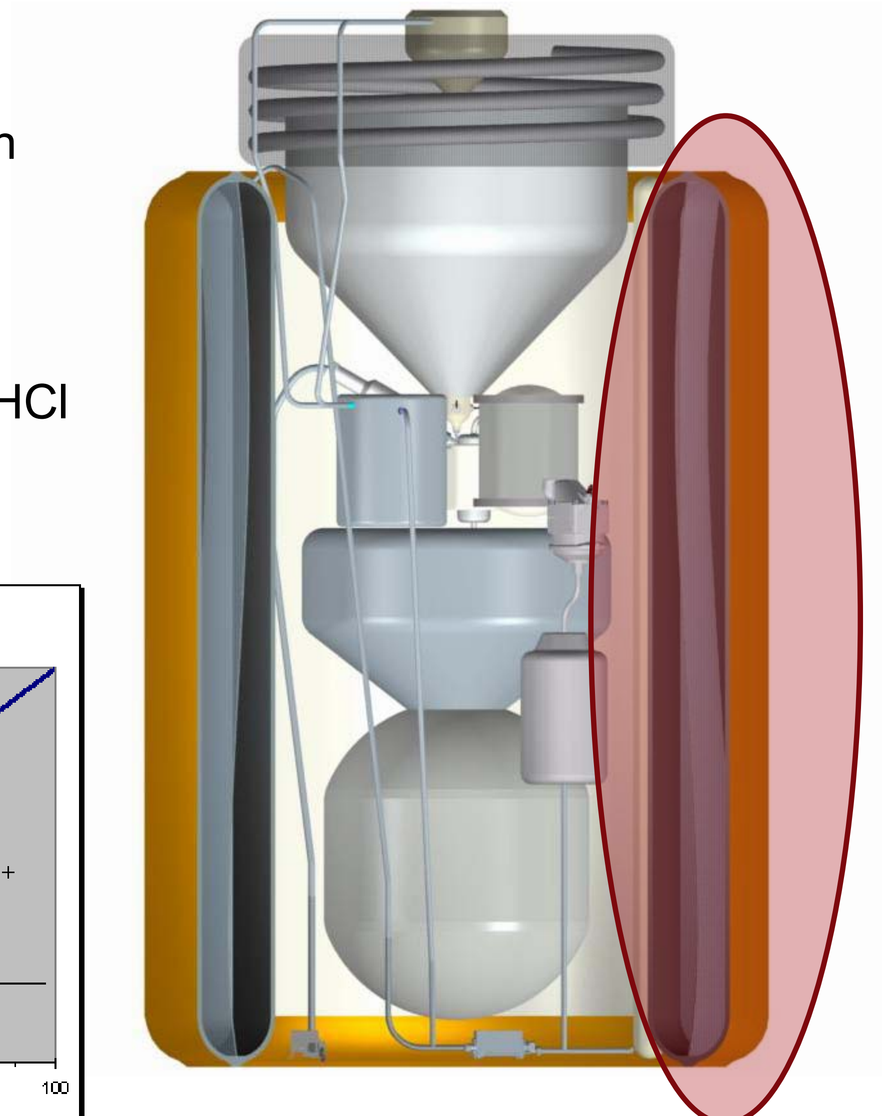
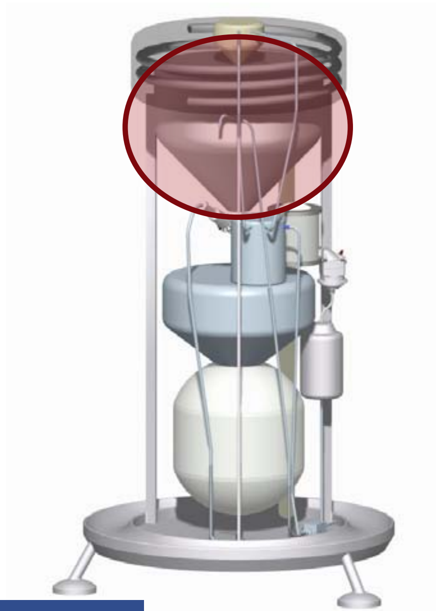
- Toroid-cylinder with bladder
- H_2O_2 + H_20 on inside, H_2O collection on outside
- Largest volume component
- Key issue = compatibility with HBr and HCl (from synthesis reactor) and thermal management

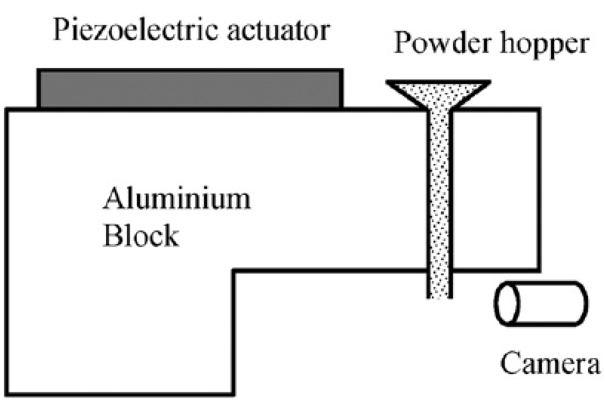


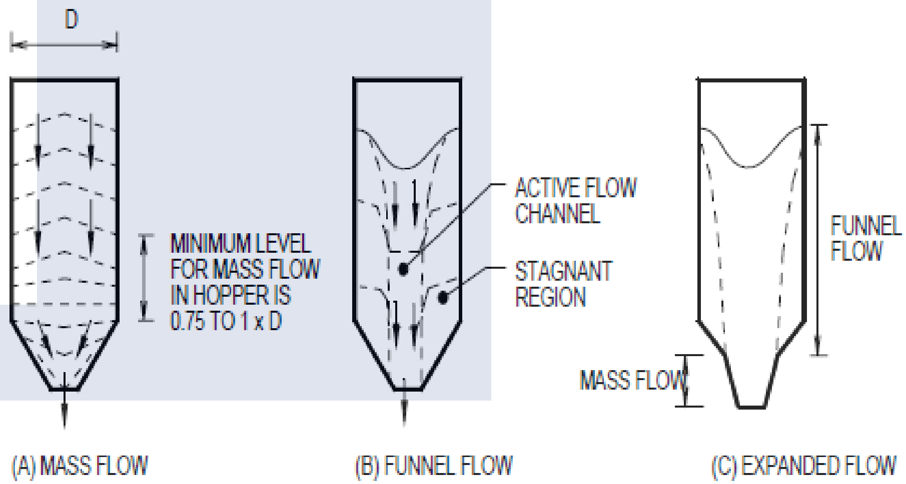


Magnesium Hydride Storage

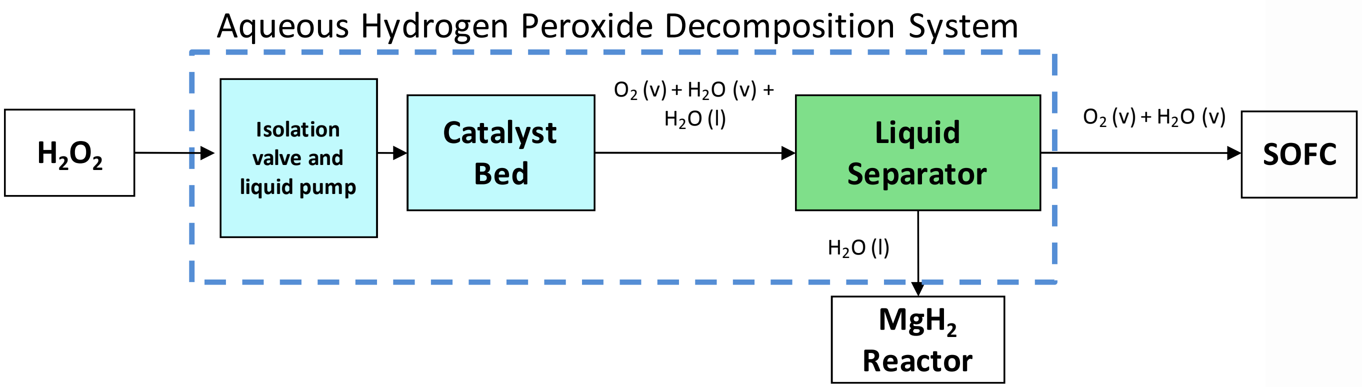
- Dry powder hopper
- Ultrasonic micro-dispenser
- Vibration-assisted flow
- Key issues – low gravity and dispense to pressurized reactor

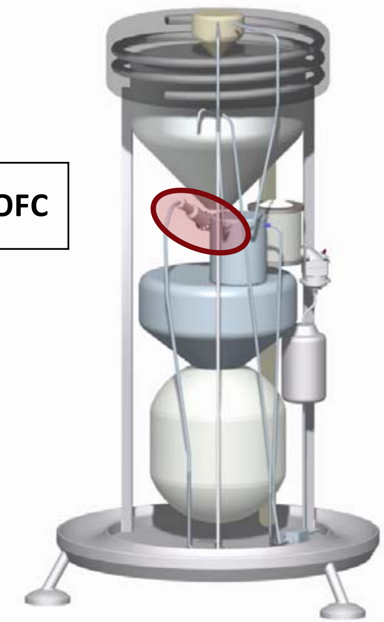




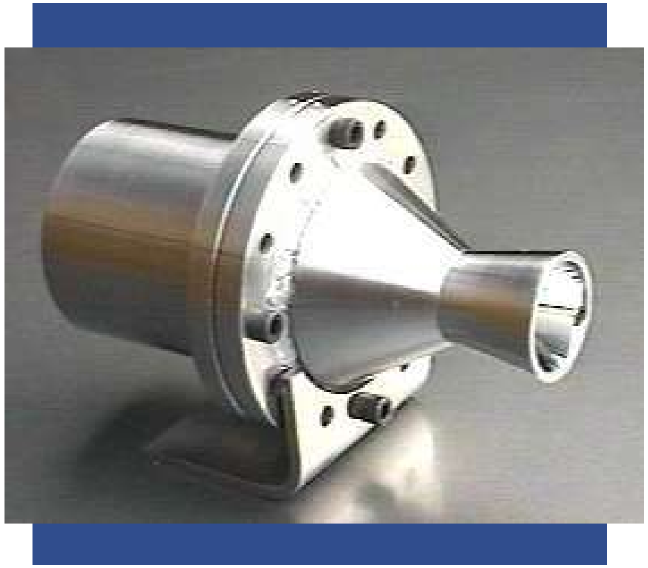


Peroxide Decomposition System





- Passive transition metal catalyst bed similar to peroxide monopropellant rockets
- Exothermic decomposition reaction
- At < 67% concentrations, temperature is limited to saturation at set pressure
- Product (<67%) is O_2 and high quality steam
- Gravity-based liquid/water separator



Magnesium Hydride Reactor

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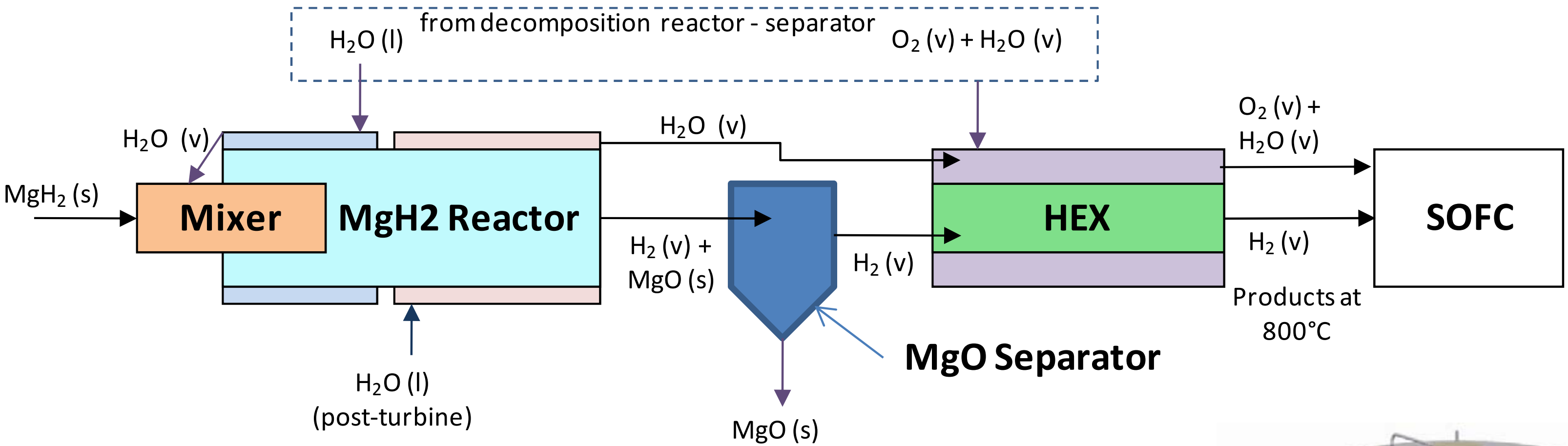
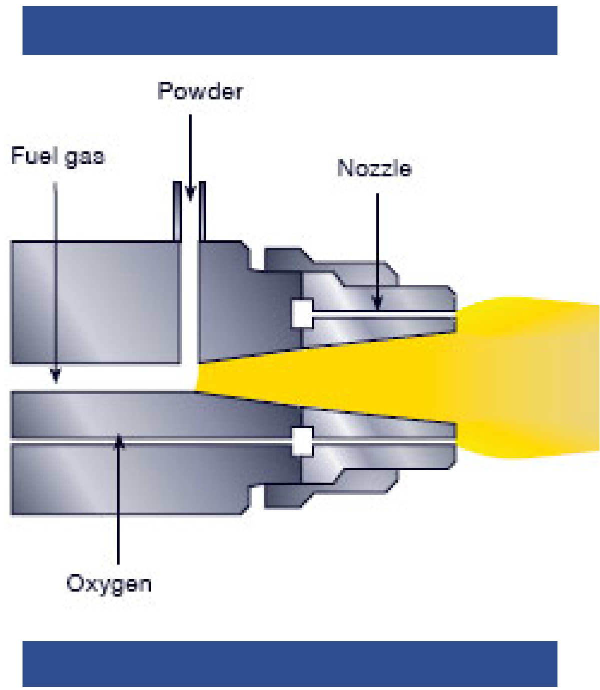
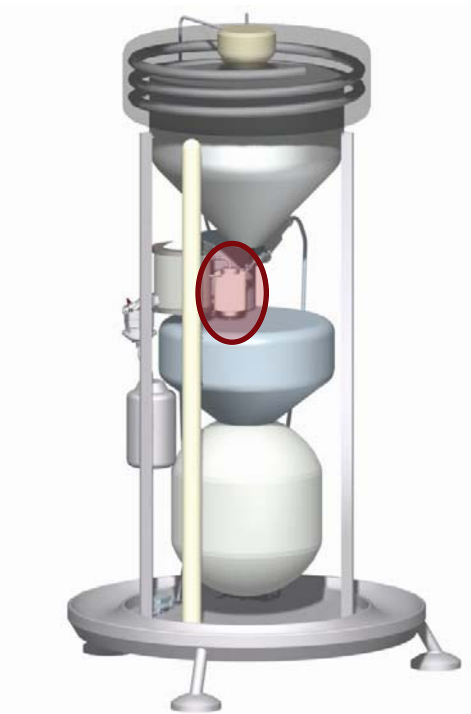


- Based on powder/flame spray gun technology
- Key is mixing efficiency and residence time to complete reaction





Solid Oxide Fuel Cell (SOFC)

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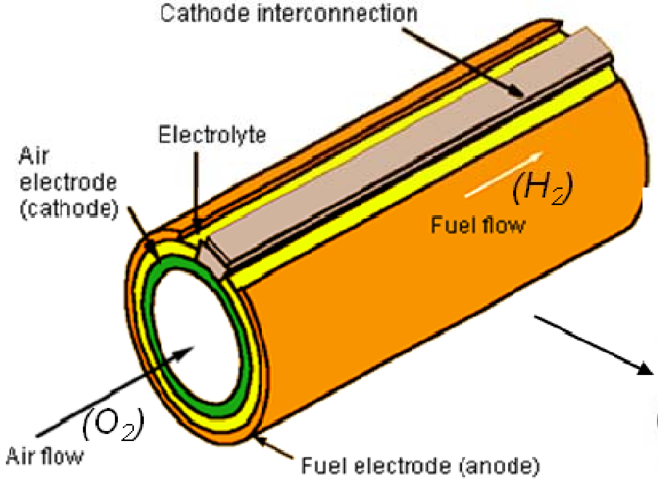
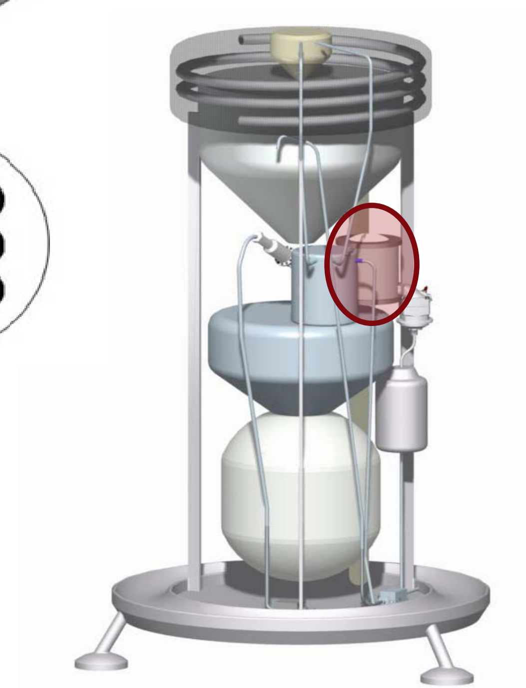
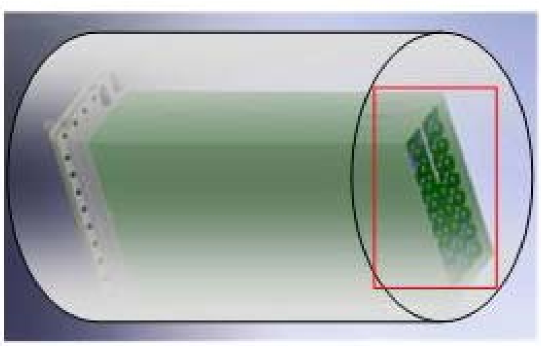
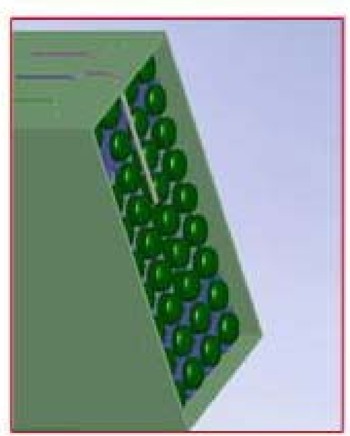
- Accumetrics cylindrical configuration is baseline



Siemens Cylindrical-tube SOFC Technology







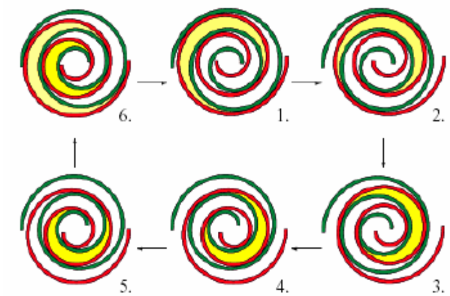
Nighttime Waste Heat Recovery - Microturbine

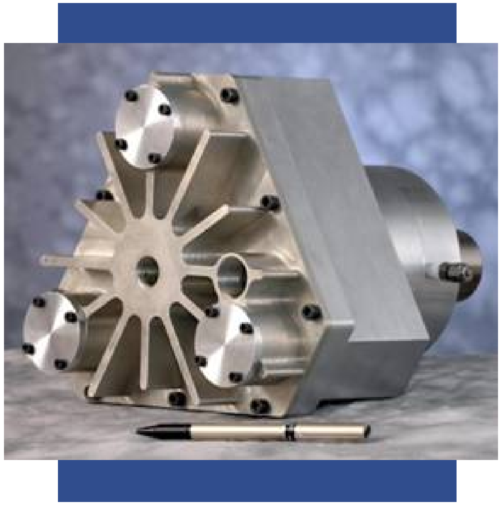
- Microturbine has highest power to weight
- We need Pin/Pout = 270 to maximize power output
- 40% efficiency today, but we can sacrifice weight for more efficiency for TRESS
- M-DOT 500 W product is selected departure point

DARPA-Funded Microturboalternator for Portable Remote Electric Power

Other Power Generation Options Considered

- Scroll expander offers 70% efficiency, however pressure ratio is limited
- Multiple units in series possible





- NASA Stirling engines for radioisotope systems
- 38% efficiency for 850°C to 90°C demonstrated

High Pressure Water Electrolyzer

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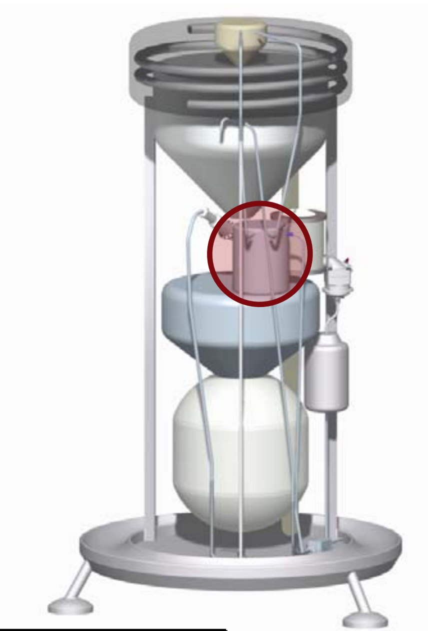
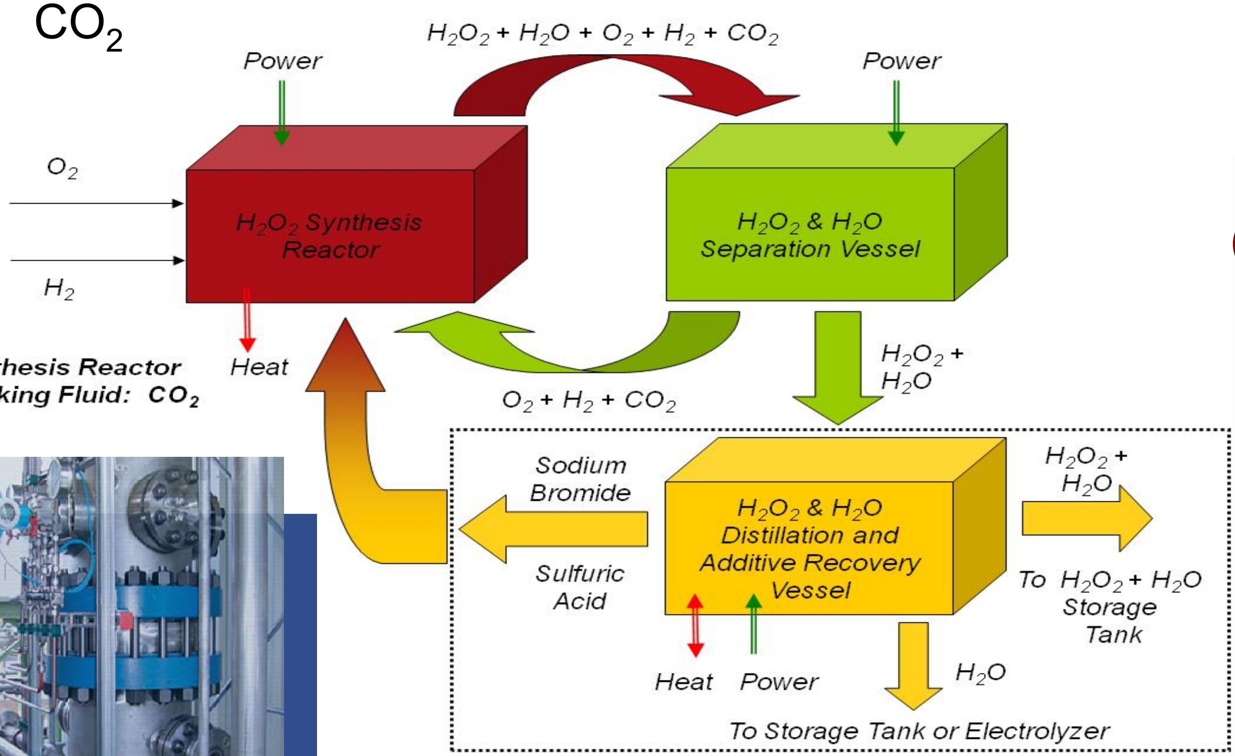
- Giner Electrochemical Systems 1,200 psi high pressure electrolyzer is baseline point of departure
  - NASA GRC and DARPA funding
  - Eliminates need for O_2 and H_2 compressors for H_2O_2 synthesis system

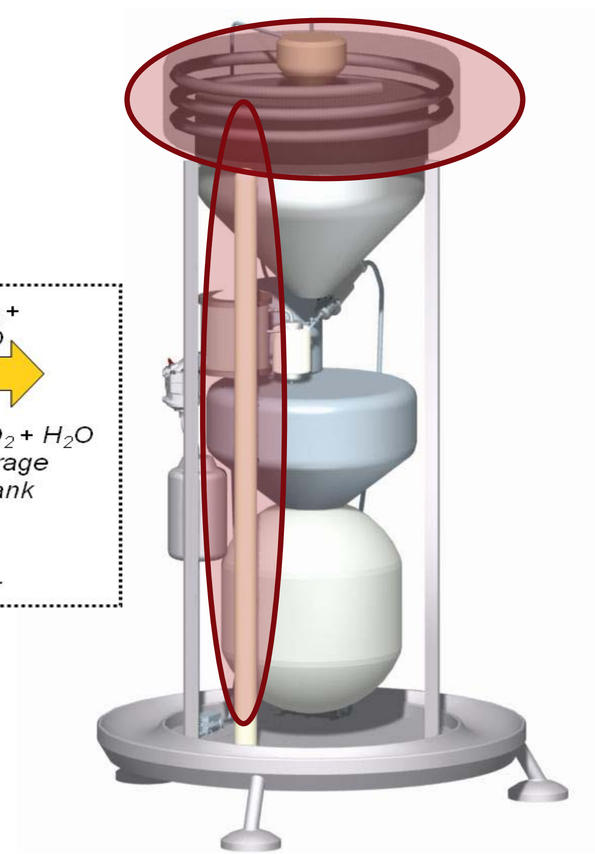


	Prototype
Specific power (W/kg)	386 (5100 Watts/13.2 kg)
Pressure (kPa gage)	8245 (1200 psig)
Efficiency at design point (at Higher Heat Value basis)	83.20% (@700 mA/cm2)
Efficiency at 25% Imax (HHV basis)	86.40%
Efficiency at 50% Imax (HHV basis)	87.60%
Efficiency at 75% mA/cm2 (HHV basis)	86.00%

Aqueous Hydrogen Peroxide Synthesis

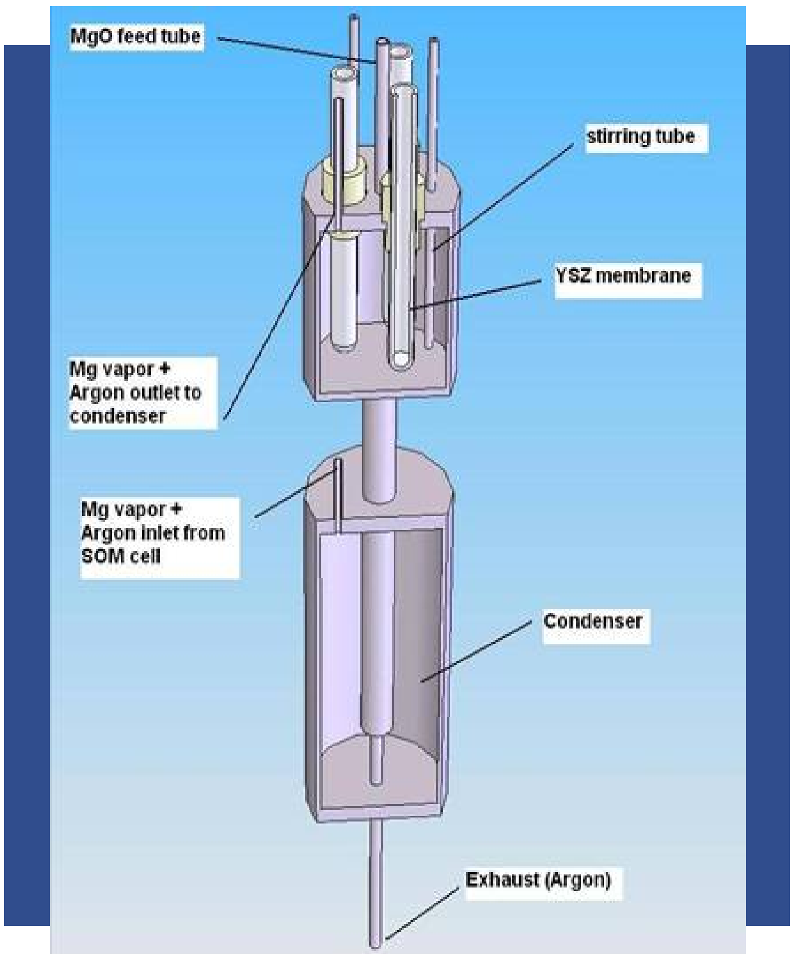
- Headwaters Technology Innovations direct synthesis process is baseline
  - Industrial process uses methanol as substrate, TRESS uses supercritical CO_2

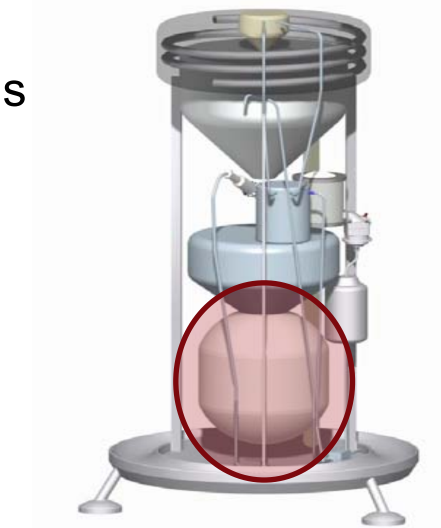


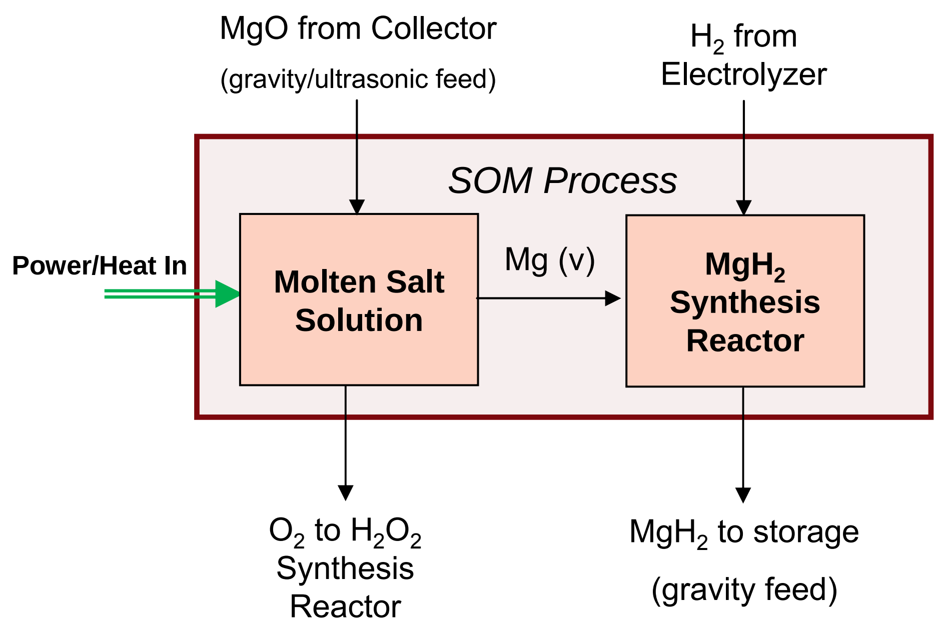


MgH_2 Regeneration System

- Boston University solid oxide membrane (SOM) process is baseline for MgO decomposition

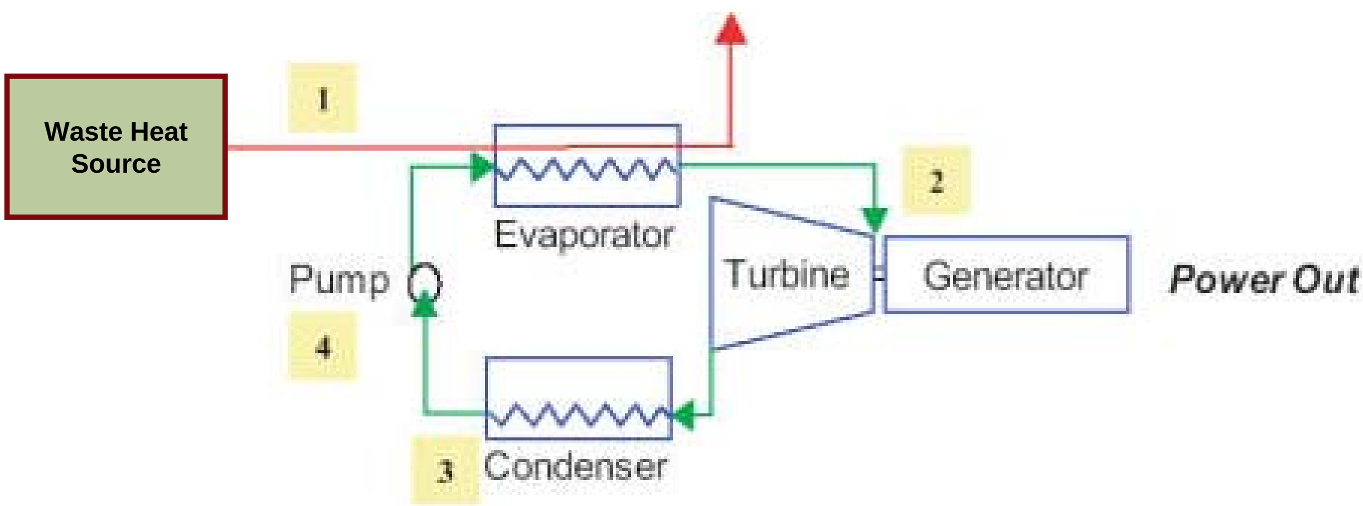






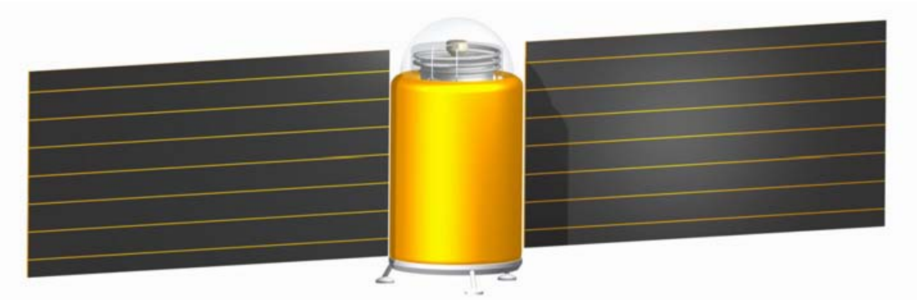
Possible Organic Rankine Cycle (ORC) on Reactor

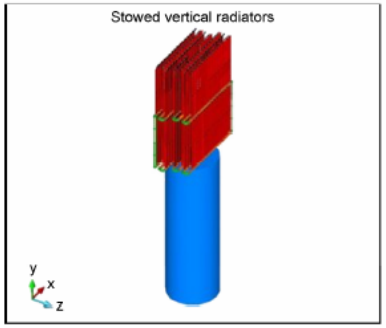
- ORC bottoming cycle may be used to extract additional energy from H_2O_2 synthesis reactor cooling loop
- Use of second fluid and temperature difference from reactor (1,150°C) to shaded lunar heat sink
- Low efficiency expected due to indirect heat exchange (~20%), but small system does not add significant weight

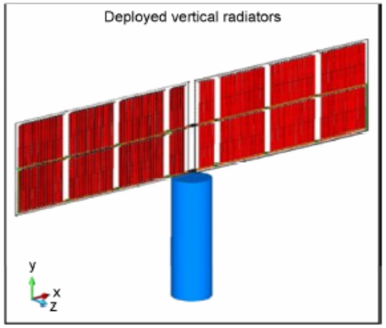


Heat Rejection Scheme

- NASA CR – 2006-214388[1] describes a potential system for heat rejection of temperatures in the range ~ 450K (177°C)







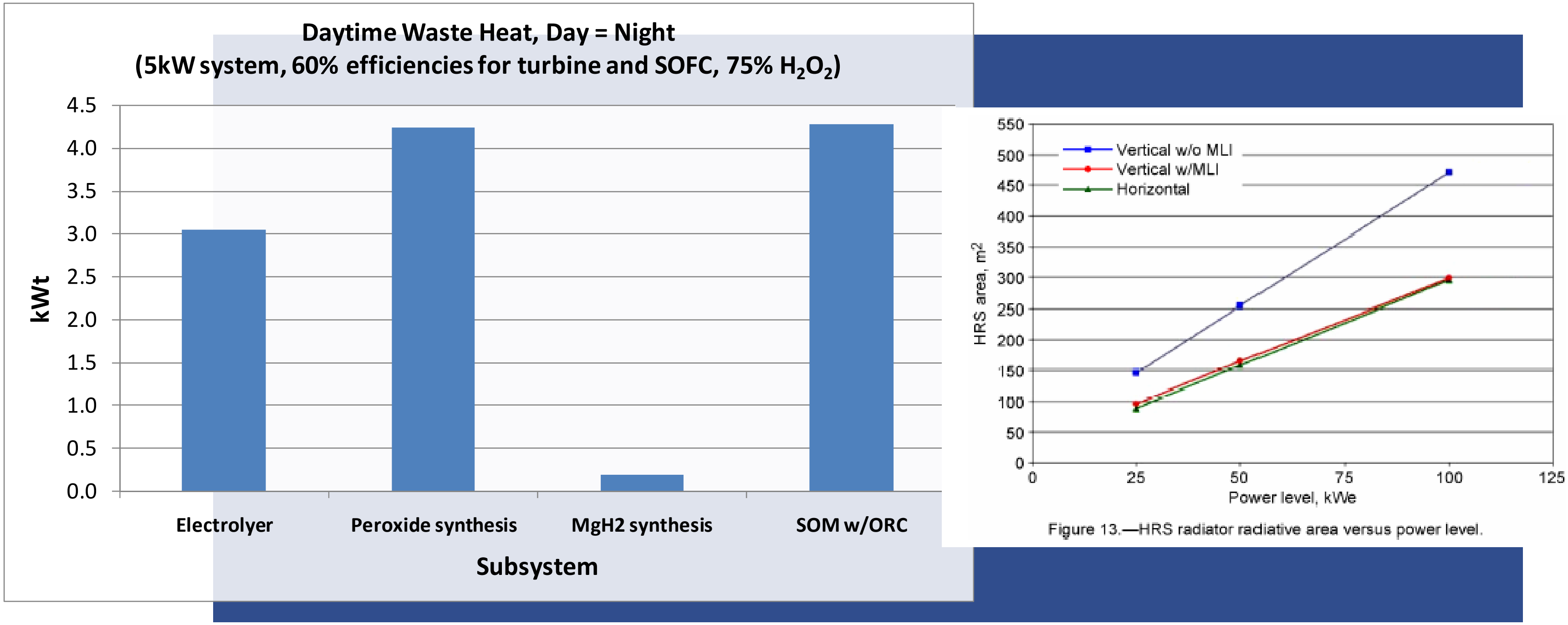
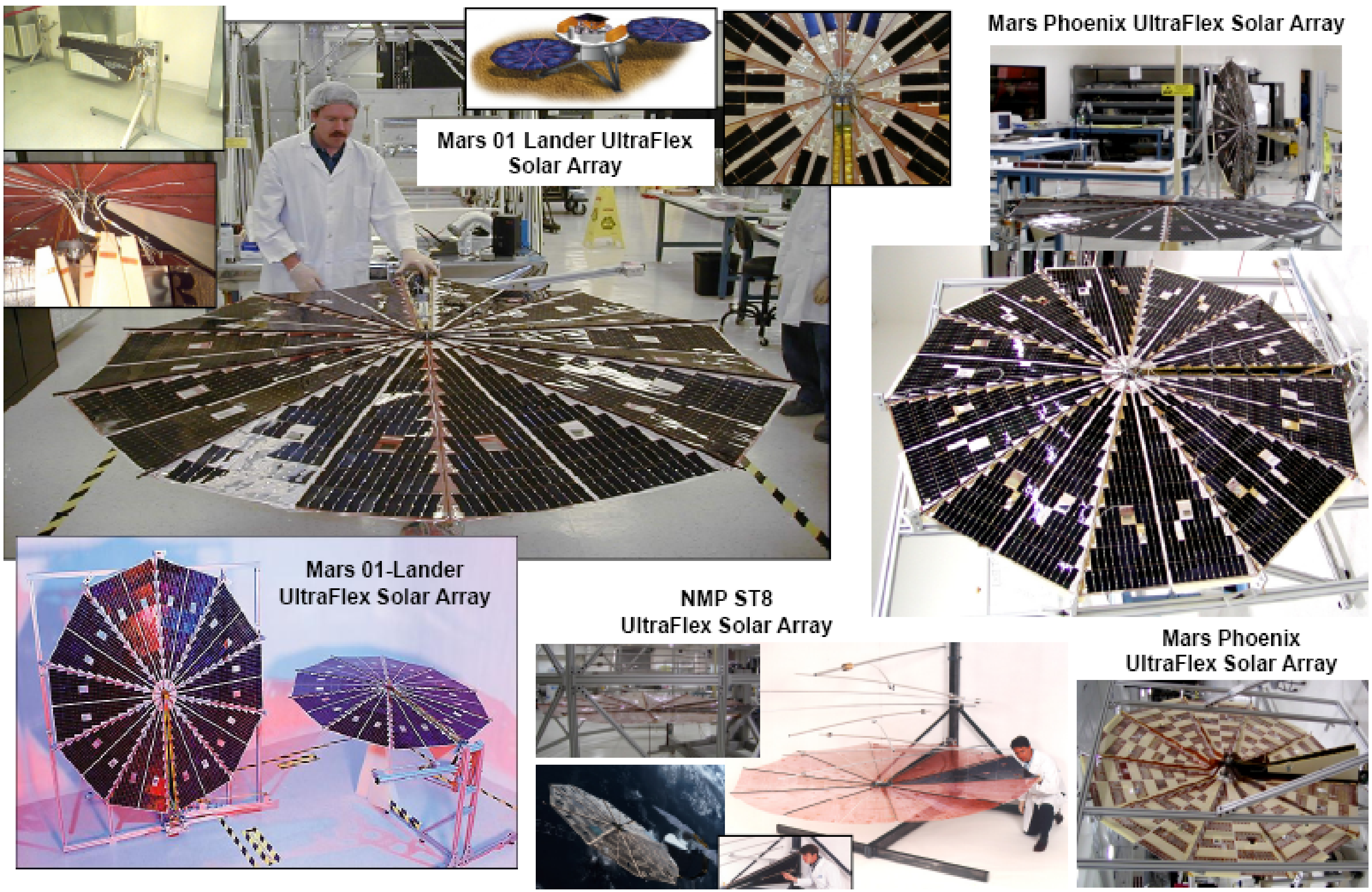


Figure 13.—HRS radiator radiative area versus power level.

[1]*NASA CR – 2006-214388, Heat Rejection Concepts for Lunar Fission Surface Power Applications, J. Siamidis*

ATK Deployable Solar Arrays

- A~6 meter diameter single-wing UltraFlex unit of 14 to 18 kW will be able to provide the necessary power for the daytime regeneration cycle of TRESS



Top Subsystem Risks

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Risk Items	Effect(s)	Proposed R&D Activities
Contamination of H_2O_2 with trace quantities of HBr and HCl	Corrosion of catalyst and reduced life of subsystem.	Experimental verification of material life with trace quantities of the additives
Ineffective gas phase MgH_2 synthesis	Incorrect chemistry	Not typically done with gas phase Mg – bench-scale tests to verify
Inefficient mixing of powder and steam	Incorrect chemistry results in low H_2 yield and undesired products	Extensive design and test of system. Leverage experience from flame spray industry
Accurate control of powder dispense in reduced gravity and low temperature	Non-uniform dispensing results in incorrect chemistry and thermal balance for system	Leverage experience from pharmaceutical industry. Carefully calibrate system
Backflow of steam due to powder dispense to pressurized reactor	Reaction in powder hopper	Backpressure hopper to above steam pressure (not desired). Supersonic injection (ejector) similar to HVOF flame spray.
HBr + HCl contaminants in MgH_2 reactor	Potential creation of unwanted compounds (e.g. $MgCl_2$ and $MgBr_2$)	Assess with bench-scale tests
SOM Containment Vessel Corrosion	maintenance, life	Investigate alternatives- material optimization, coatings, alloys..; surface temp.
SOM YSZ Membrane Durability	Life, efficiency, maintenance, durability	Examine post-exposure mechanical and physical characteristics

Top System Level Risks

Risk Items	Effect(s)	Importance/ Likely-hood	Technical Risk	Proposed R&D Activities
Inaccuracy in flow control, particularly during system transients	Reduced efficiency, offset thermal balance, unwanted products can accumulate contaminants	High	High	Comprehensive closed-loop control architecture development. Extensive testing and sensitivity examination
Thermal balance variations, particularly during transients	System efficiency, weight, life	High	Med	Thermal controls development and testing – sensitivity assessment. Environmental tests
Accumulation of contaminants	Efficiency, life reduction	High	High	Subsystem testing to insure purity, system testing to assess impacts

TRL Assessment

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System	TRL Today (on Earth)	TRL Today (lunar)	Risk to TRL 6 by 2015
H_2O_2 Storage	9	2	L
MgH_2 Storage	9	2	L
H_2O_2 Decomposition Reactor	9	3	L
MgH_2 + H_2O Reactor	4	2	L
SOFC and Turbine	5	3	M
Water Electrolysis	9	6	L
MgH_2 Synthesis	3	1 - 2	M/H
H_2O_2 Synthesis	9	1 - 2	M/H
System Integration and Operation			H

Figure of Merit Sensitivity Analysis

- Variables used in parametric analysis:
  - Percent hydrogen peroxide concentration in water (50% and 75%)
  - System power level (2, 3.5, and 5 kW)
  - System energy storage (100 kWh to 2,000 kwh) or up to 400 hours
  - Regeneration time as a function of power generation time (1X and 2X)
  - SOFC efficiency (45% to 60%)
  - Nighttime waste heat efficiency
- Key figures of merit:
  - System flow rates
  - Overall TRESS system mass
  - Energy-in/energy-out “round trip” efficiency
  - Power-in requirements
  - System mass distribution by major subsystem

Overall System Energy Efficiency with ORC

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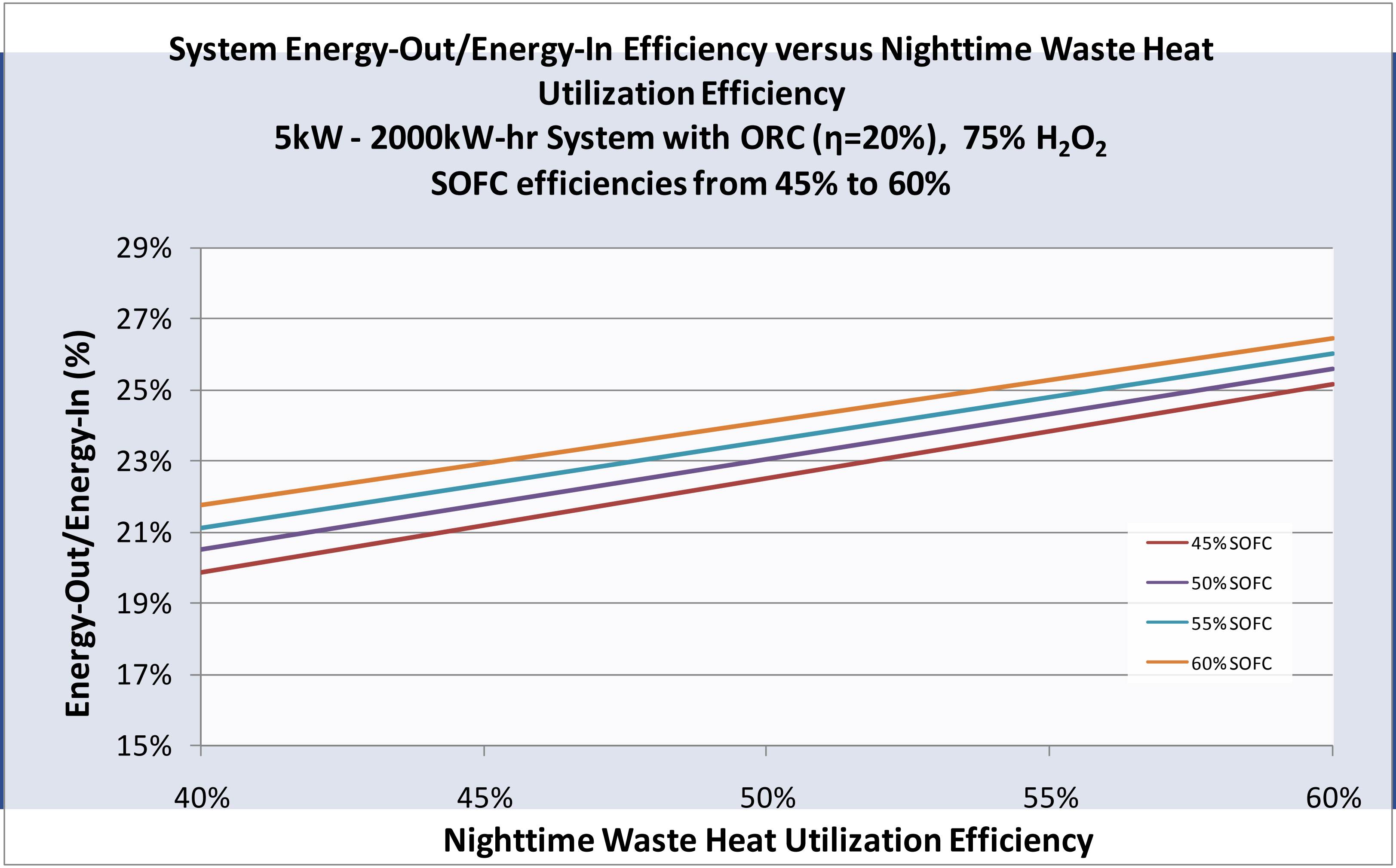
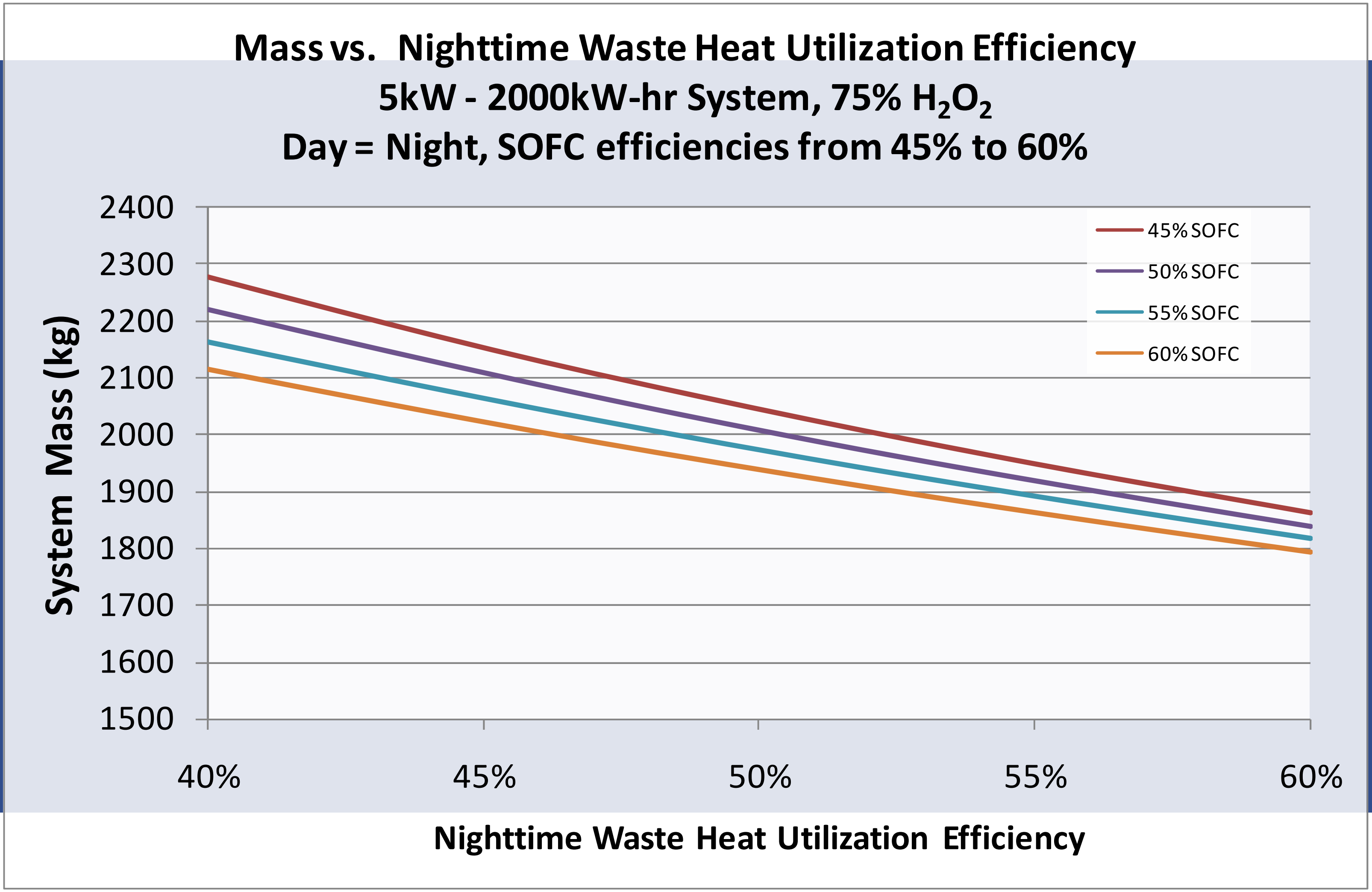
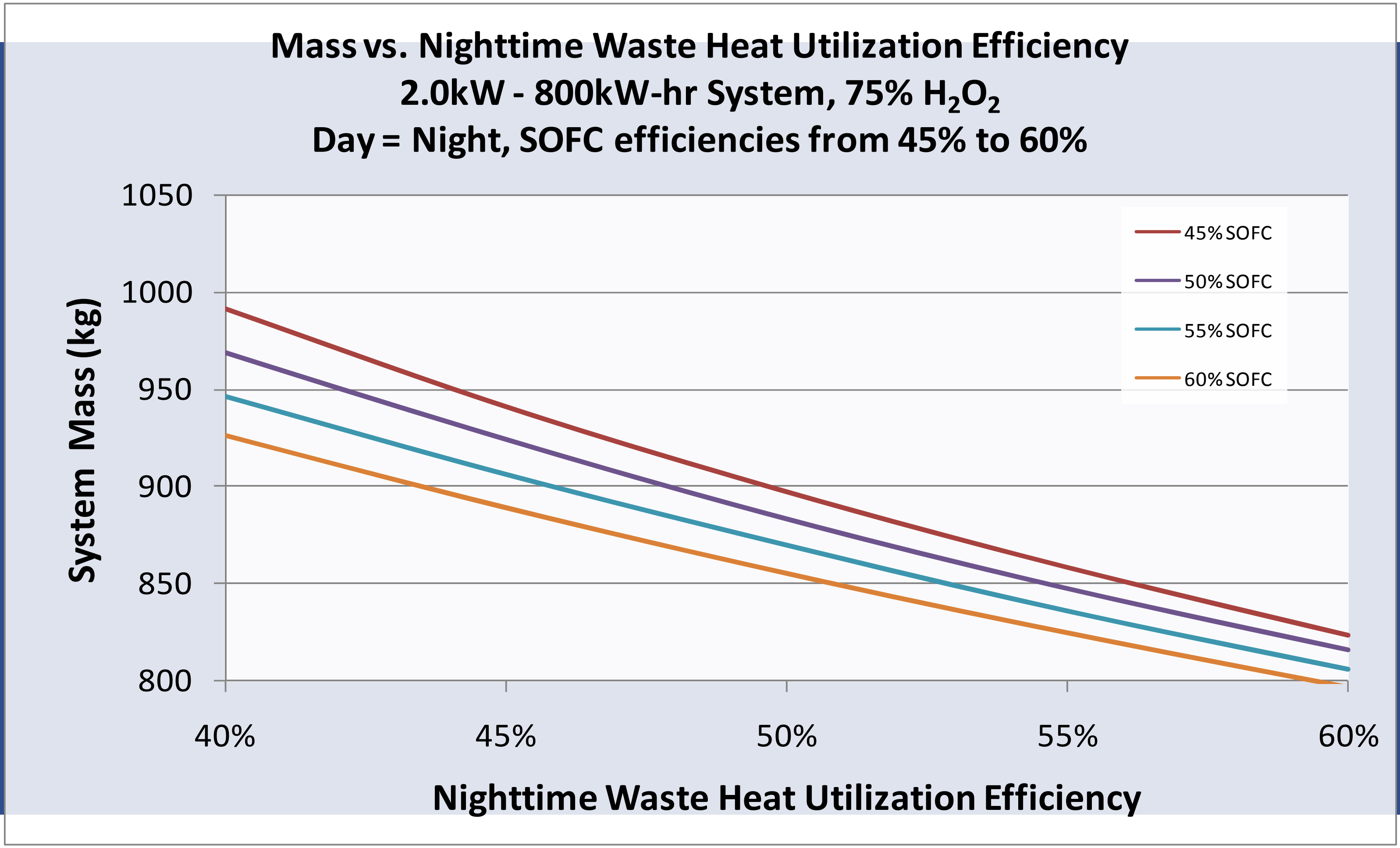


System Mass Sensitivity (5 kW, 75% Peroxide)



System Mass Sensitivity (2 kW, 75% Peroxide)



Daytime Waste Heat (75% Peroxide)

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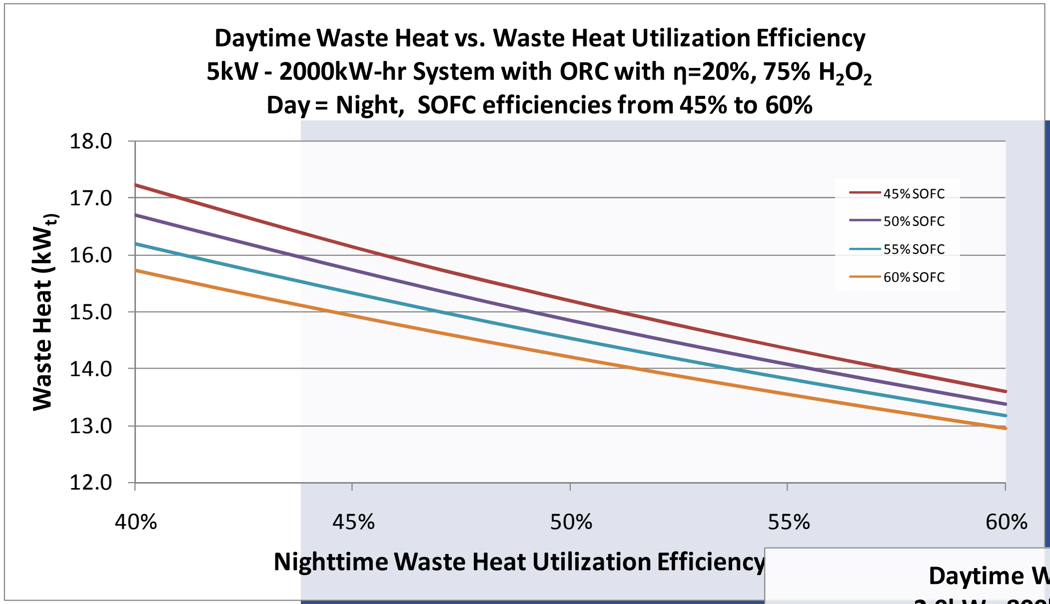

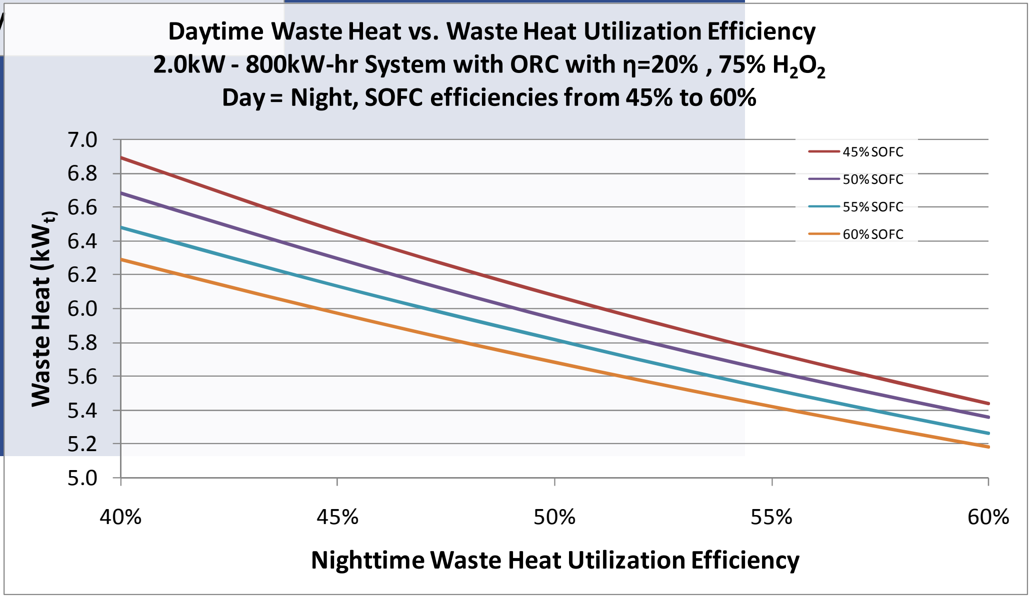

Daytime Waste Heat (55% Peroxide)

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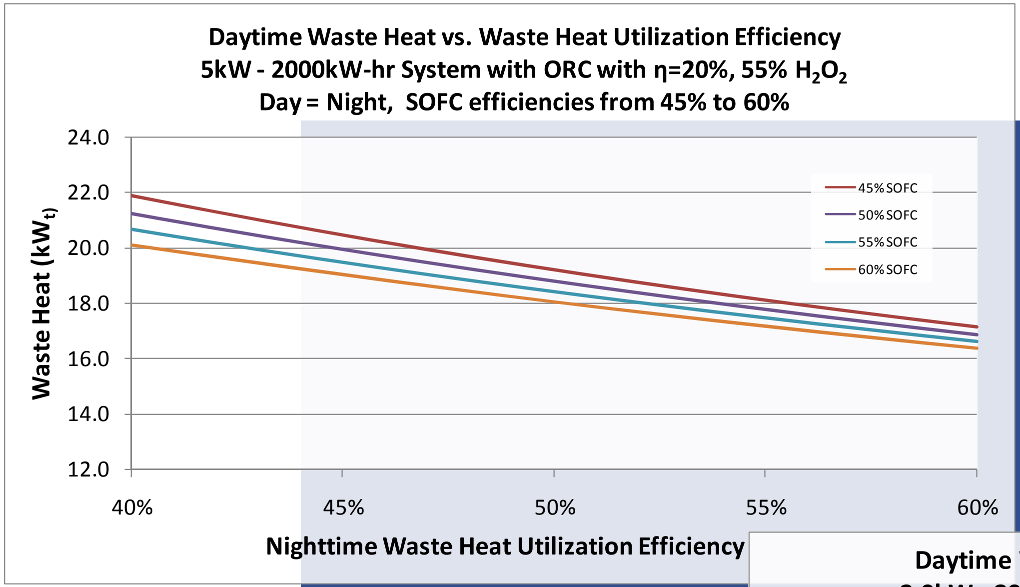
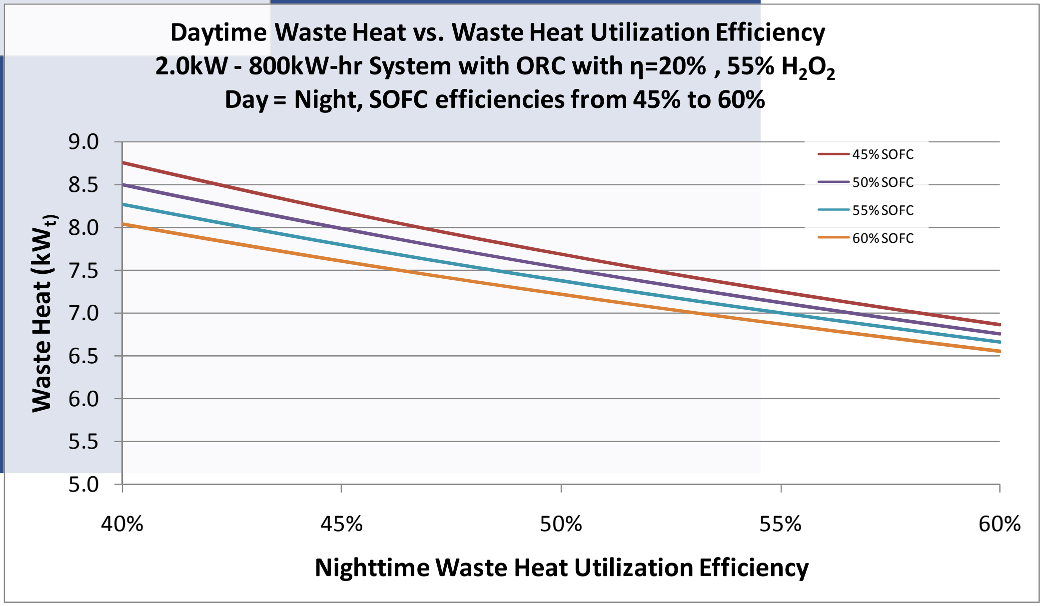
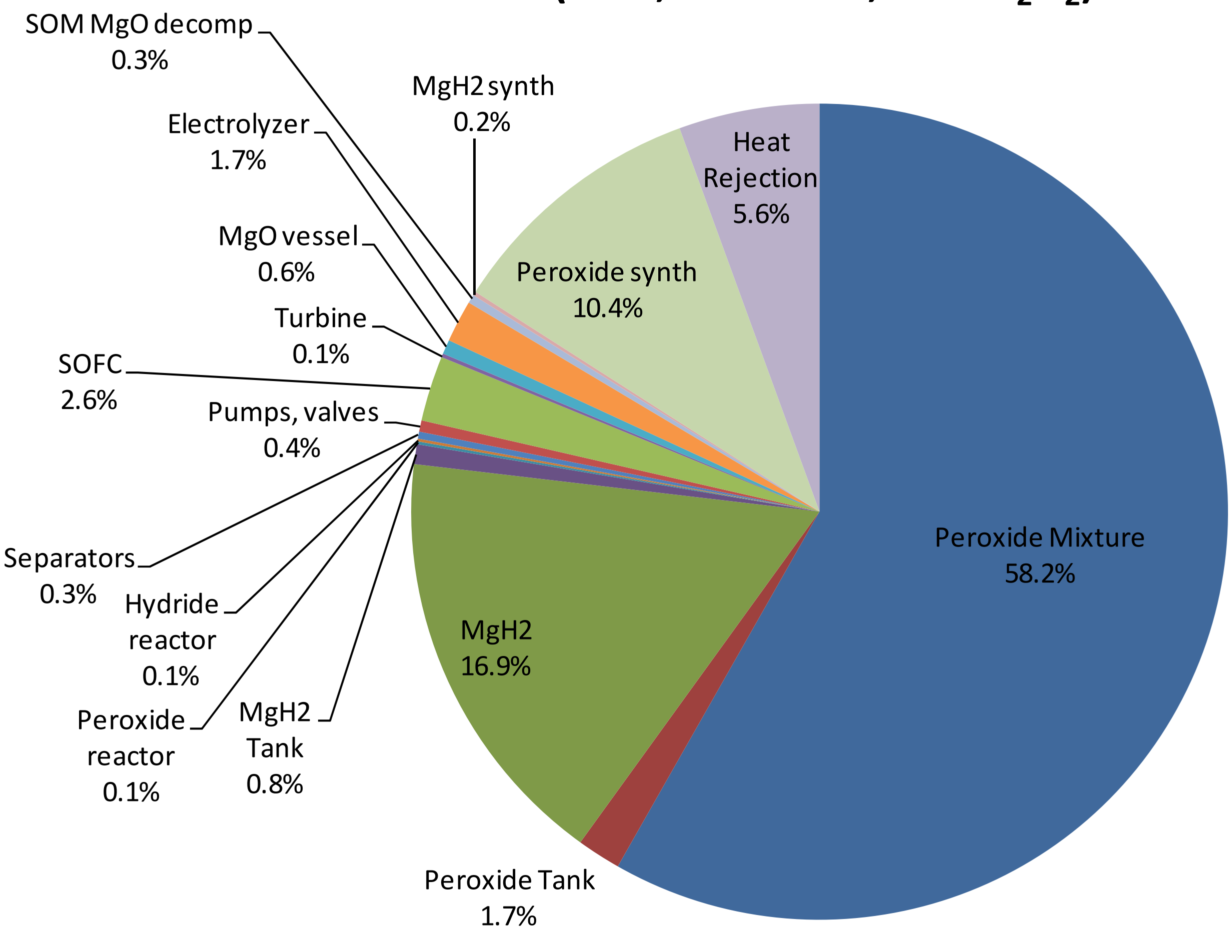
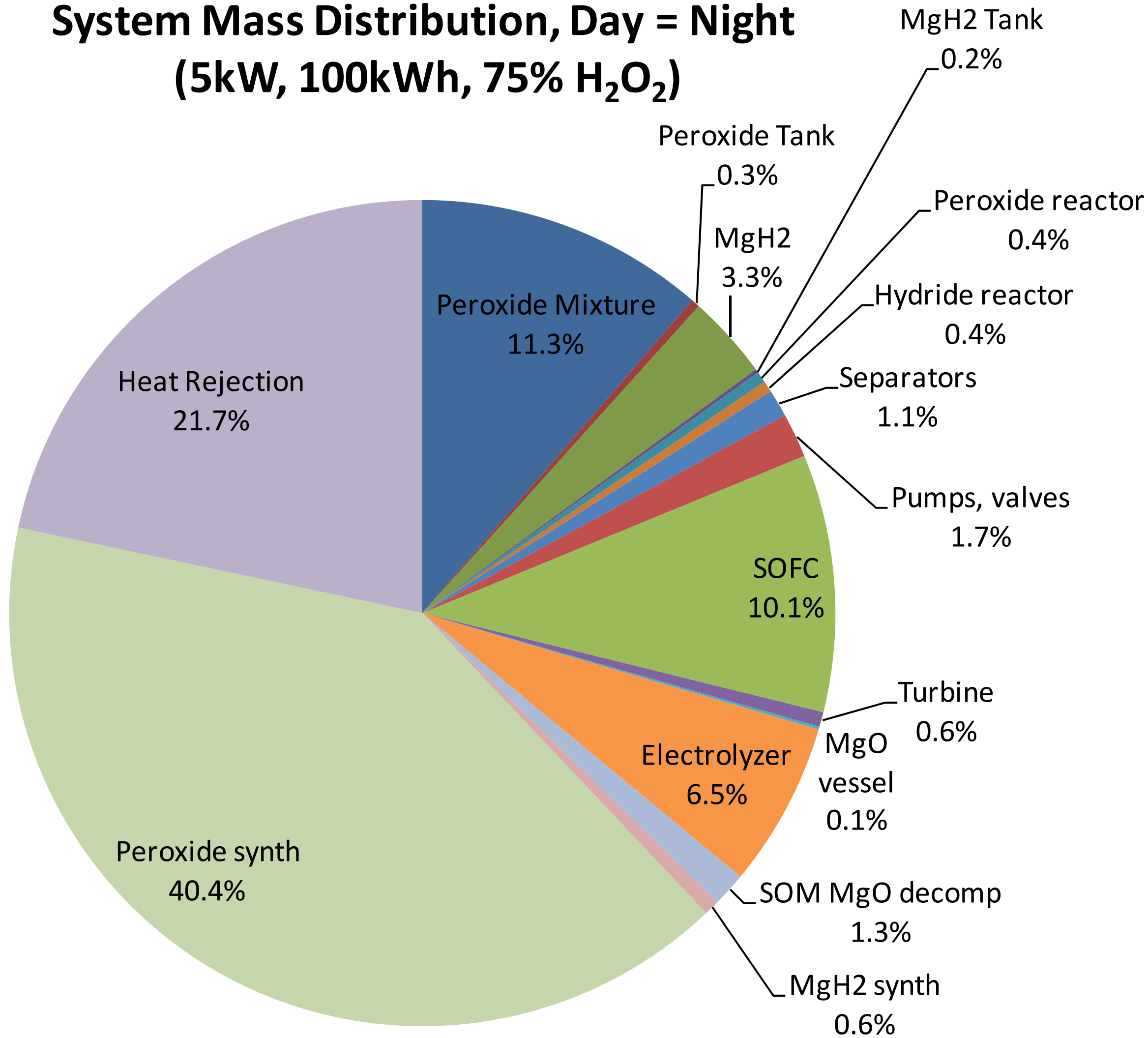


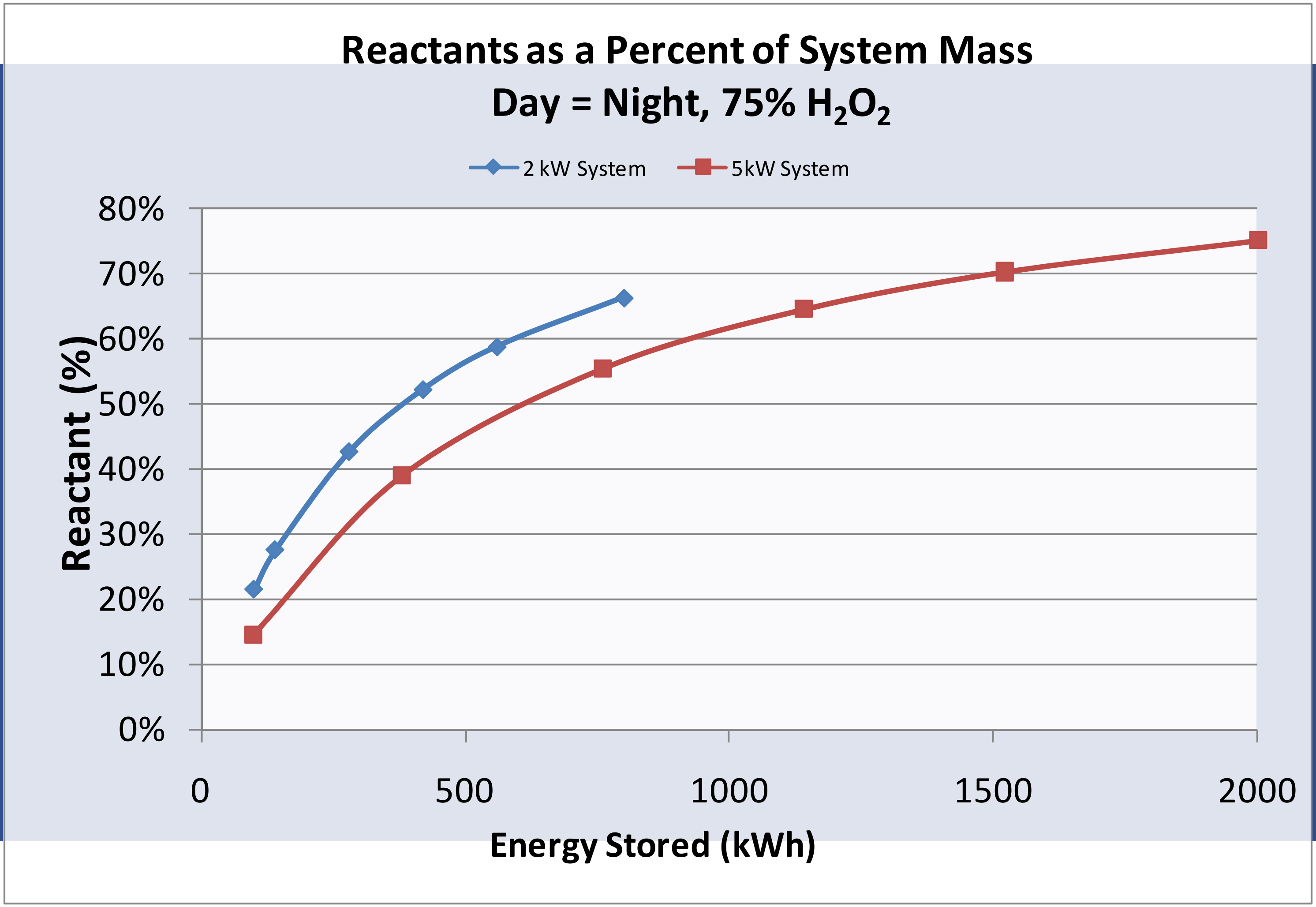


System Mass Distribution, Day = Night (5kW, 2000kWh, 75% H_2O_2)



System Mass Distribution, Day = Night (5kW, 100kWh, 75% H_2O_2)




Reactants as a Percent of System Mass
Day = Night, 75% H_2O_2
2 kW System
5kW System
Reactant (%)
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
500
1000
1500
2000
Energy Stored (kWh)

Key Results Summary

- System is characterized by high energy density
  - ~1.1 kWh.kg for complete TRESS
  - ~1.4 kWh/kg for power generation only
- As expected, high concentrations of peroxide are favorable
  - Less water to store and regenerate in peroxide mixture
- Reactant storage is key mass and volume driver
  - Efficiency is key for power gen components – mass is secondary (or lower)

100 W TRESS-derived Power Sources (ILN)

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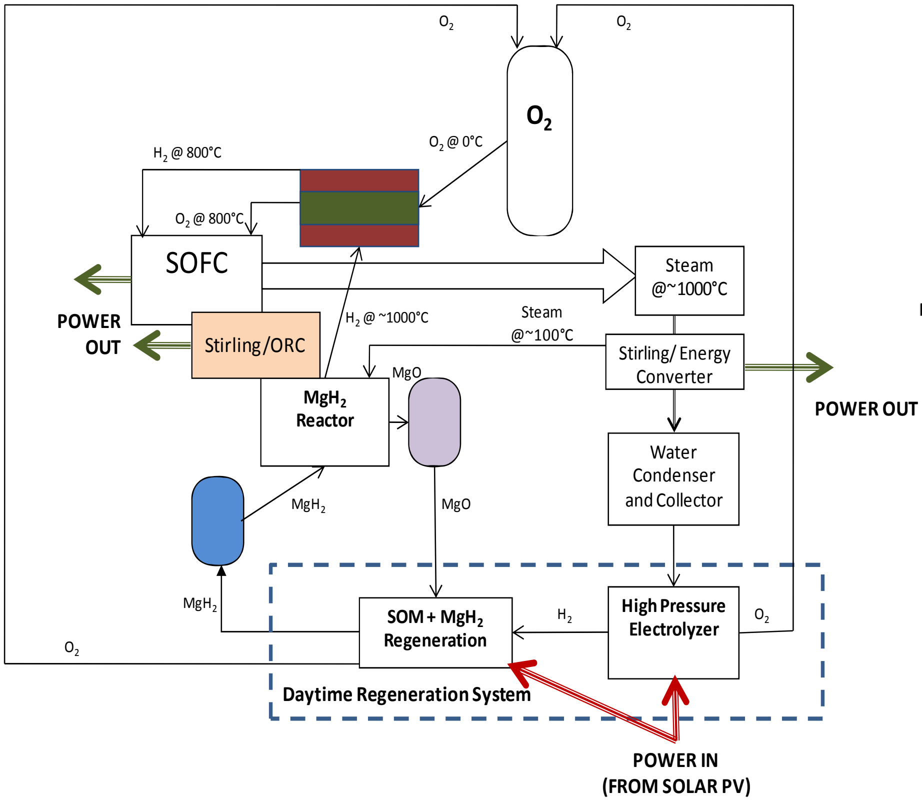
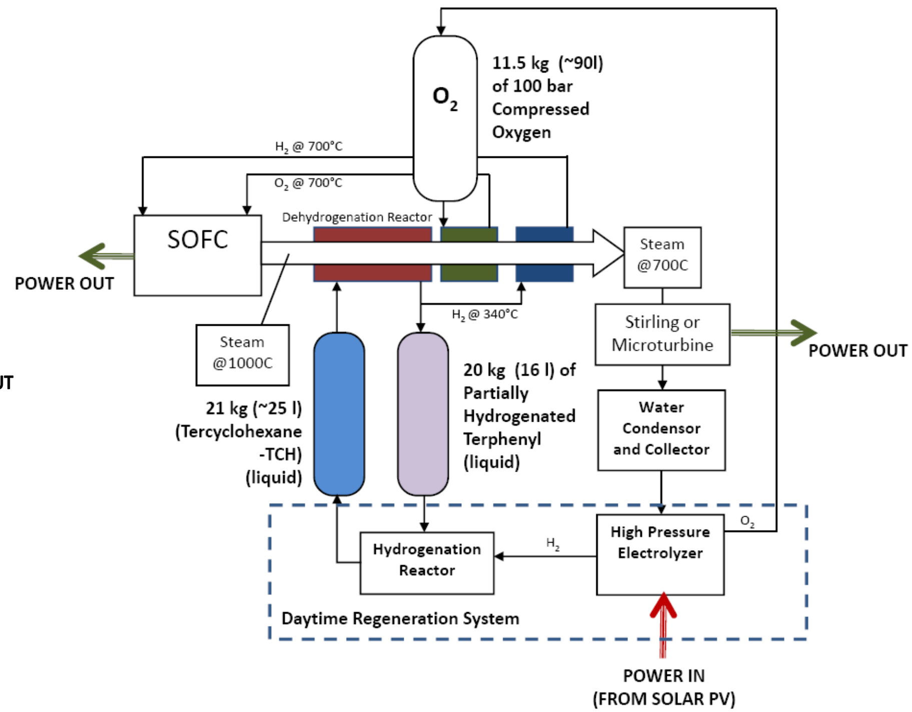
Operational Time 336 hours

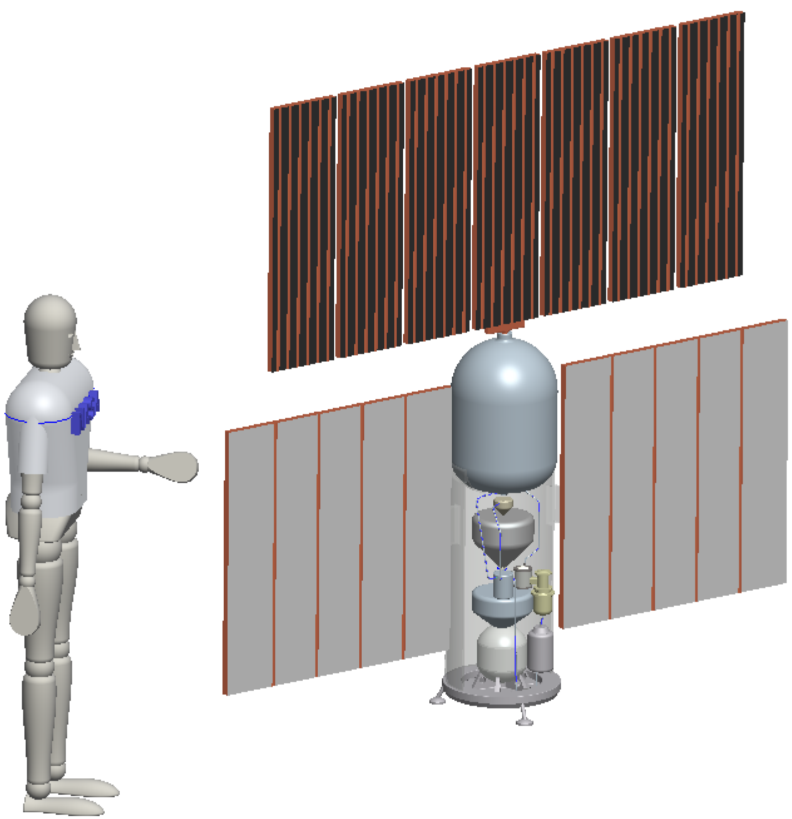


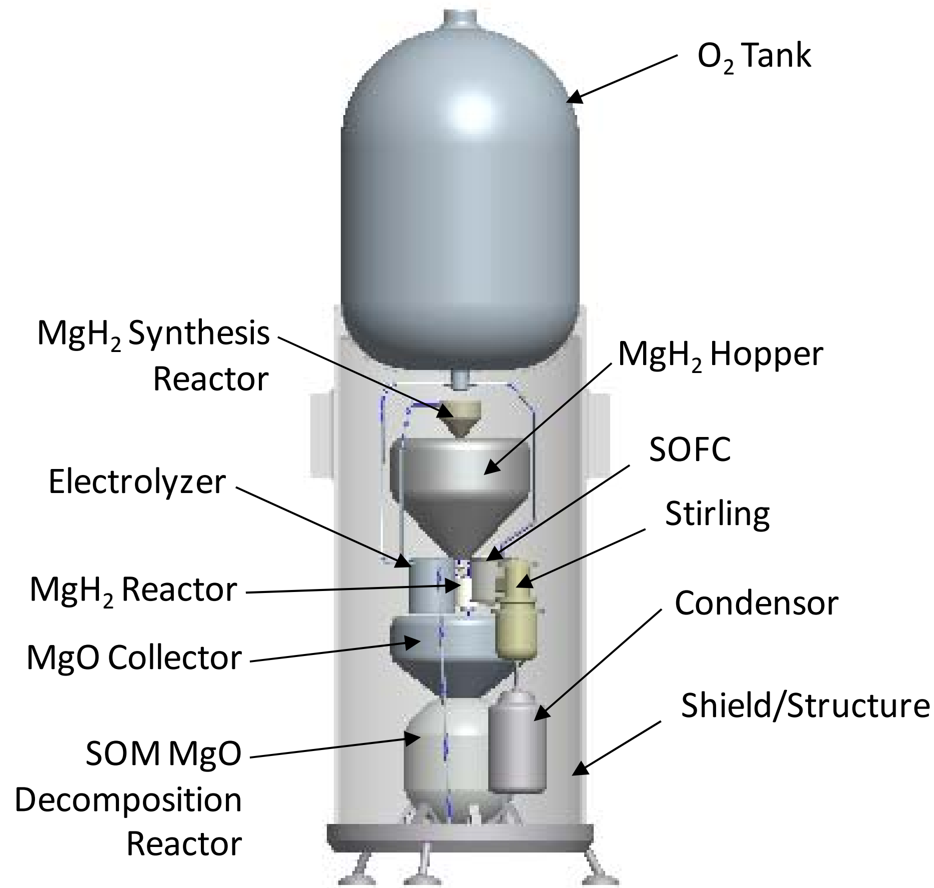
MgH_2/O_2 System
Weight ~35kg; Volume ~140 l



TCH/O_2 System
Weight ~50kg; Volume ~220 l

100 W MgH_2/O_2 System Configuration





ILN TRESS Variants – Mass Distributions

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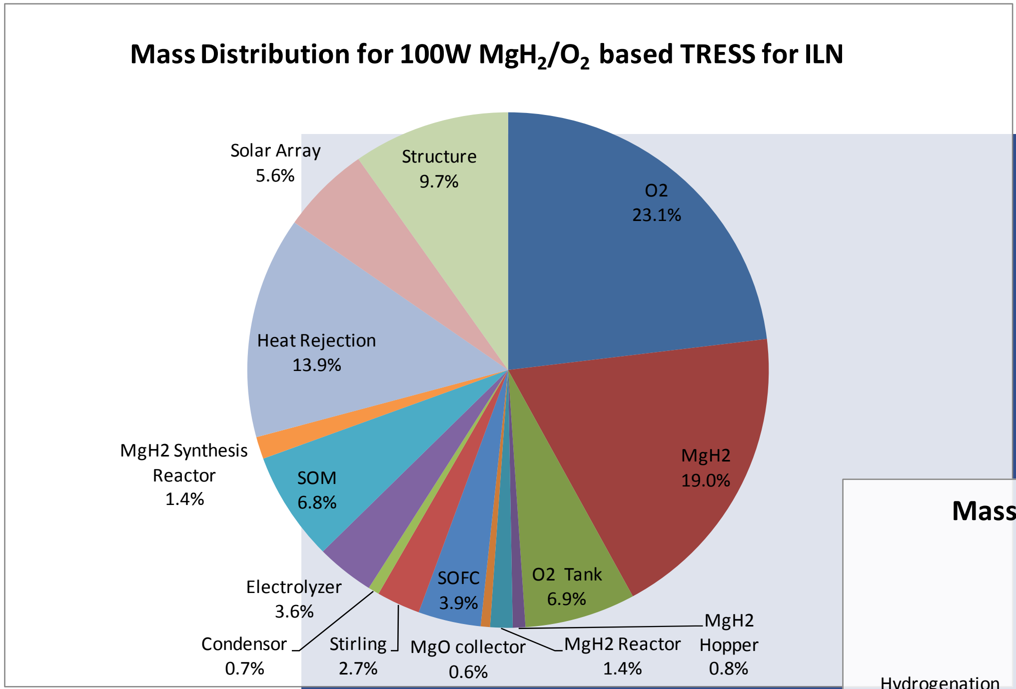

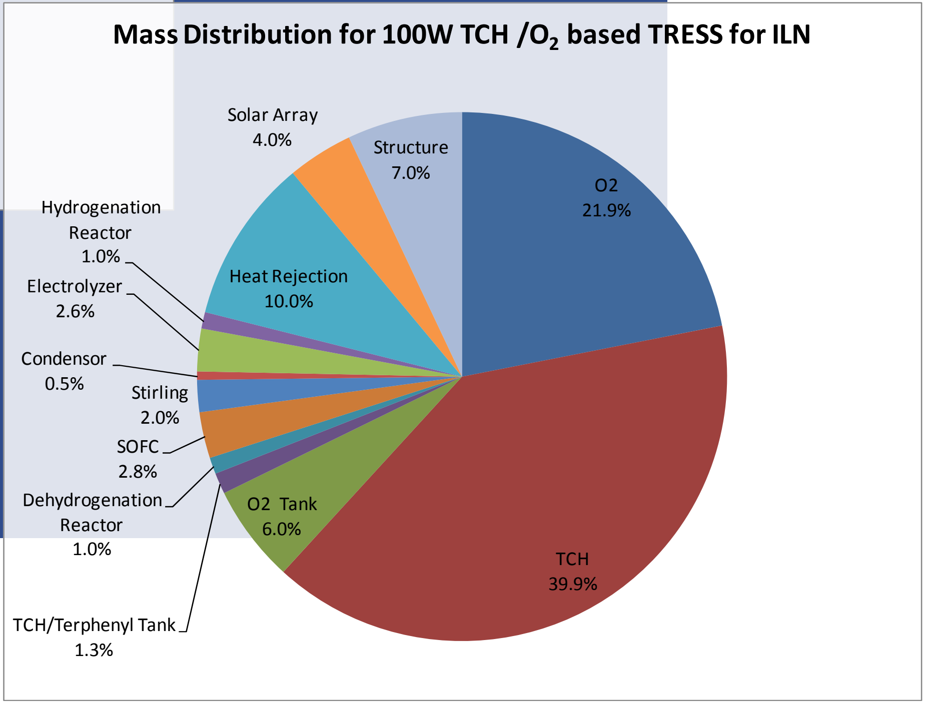

TRESS Summary

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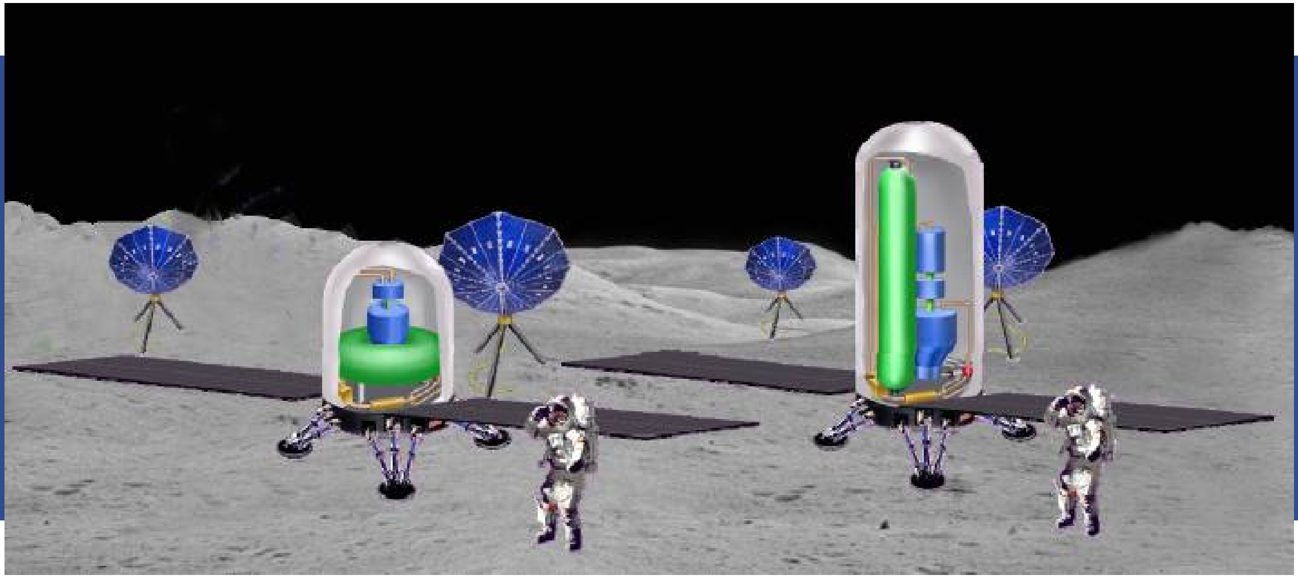
- Our Thermochemical Regenerative Energy Storage System (TRESS) is a promising candidate to meet NASA's requirements in a highly compact, efficient package
- The system performance and form factor is superior to batteries and H_2 –O_2 regenerative fuel cell based systems
- TRESS is highly compatible with future in-situ resource utilization (ISRU) for added long-term benefits
- ATK has committed significant funding to the underlying CHOSS system development



Thank You!